MODAL ANALYSIS FOR VOLTAGE STABILITY AND DESIGN OF FIXED AND DYNAMIC SHUNT VAR COMPENSATION FOR THE NORTHERN GRID OF INDIA

by

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MODAL ANALYSIS FOR VOLTAGE STABILITY AND DESIGN OF FIXED AND DYNAMIC SHUNT VAR COMPENSATION FOR THE NORTHERN GRID OF INDIA

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Certificate

It is to certify that the work contained in the thesis entitled *"Modal Analysis for Voltage Stability and Design of Fixed and Dynamic Shunt VAR Compensation for the Northern Grid of India"* by **Jainendra Singh** has been carried out under our supervision and that this work has not been submitted elsewhere for a degree

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List of Symbols

[ΔV]	Vector of bus voltage magnitudes
[ΔQ]	Vector of bus reactive power injections
[VSF]	Voltage sensitivity factor matrix
SVC	Static VAR compensator
MTDC	Multi terminal DC system
PFLOW	Power flow software
NRGI	Northern Regional Grid of India
V_{dj}	P U DC voltage at j^{th} converter terminal
I_{dj}	P U DC current at j^{th} converter terminal
V_j	P U converter bus AC voltage
R_{cj}	P U commutation resistance
a_j	Off nominal taps of converter transformer
θ_j	Delay angle (α_j) for rectifier and extinction angle (γ_j) for inverter
P_{dj}	P U real power drawn by j^{th} converter terminal
Q_{dj}	P U reactive power drawn by j^{th} converter terminal
P_{acj}	P U real power injected at j^{th} converter terminal
Q_{acj}	P U reactive power injected at j^{th} converter terminal
Q_{sj}	Fixed reactive power injection at bus j
J_R	Reduced Jacobian matrix
ξ	Right eigenvector of J_R
η	Left eigenvector of J_R
Λ	Diagonal matrix of eigenvalues of J_R
P_{ki}	Participation factor of bus k in mode i
VST	Voltage setting terminal
non VST	Non voltage setting terminal

Abstract

The Northern Regional Grid of India (NRGI) has for long been recognized as a system deficient in reactive power support and thus has experienced severe voltage disturbances and collapses in the recent years In this thesis Q V modal analysis of the NRGI system is done to (1) identify areas/buses where compensation is required using participation factor analysis (2) determine the kind of compensation i e fixed or dynamic shunt compensation and (3) determine the rating of the compensating devices (fixed capacitors and SVCs) Analysis is carried out for the base case and critical line outages Two possible SVC locations and some additional fixed shunt compensation for regions having poor voltage profiles are suggested Other alternatives for strengthening the system such as additional lines in parallel with the existing main trunk lines and series compensation of the major trunk lines are also analyzed It is concluded that dynamic shunt compensation is the best possible option available Continuation power flow analysis (using PFLOW software) is done to determine the steady state voltage stability margin of the system Any additional compensation if needed in order to maintain system voltage stability following an increase in the system loading levels is determined The thesis also shows that with just one additional SVC of adequate rating installed at Moradabad 400 kV bus voltage collapse seen in recent times can be avoided It is suggested that there is an urgent need for installing this SVC

Chapter 1

Introduction

1 1 General

Over the past several years voltage instability has become one of the major concerns of the electric utility industry Voltage stability problems are generally associated with heavily stressed systems having insufficient reactive power support Systems using long transmission lines with inadequate compensation for power transfer are highly prone to voltage instability Highly developed networks having more or less fixed generating capacities but ever increasing loading levels also experience voltage stability problems

According to a CIGRE Working Committee report [10] voltage stability and voltage instability are defined as follows

- Voltage Stability A power system at a given operating state and subject to a given disturbance is voltage stable if voltages near loads approach post disturbance equilibrium values The disturbed state is within the region of attraction of the stable post disturbance equilibrium
- Voltage Instability Voltage instability is the absence of voltage stability and results in progressive voltage decrease (or increase) If the voltage at the system buses reach unacceptable limits then a voltage collapse is said to have taken place

1 2 Factors Affecting Voltage Stability

The basic reason for voltage instability in a system is absence of sufficient reactive power support in the system Heavily loaded systems are more prone to voltage instability problems The operating characteristics of the various power system components such as the compensating devices voltage dependent characteristics of the loads generator reactive power and excitation control circuits (AVR etc) Under Load Tap Changers (ULTC) and HVDC converters connected to weak AC system play a major role in determining system voltage stability

1 3 Voltage Stability Analysis in MTDC-AC System

HVDC transmission has many advantages over AC transmission HVDC transmission gives the practical solution for bulk power transfer over long distances underground or submarine cable links The technical superiority of DC transmission makes it the obvious choice for interconnection of asynchronous AC systems operating at different frequencies power transmission into urban areas and tie line interconnections (back to back connection) Some other specific advantages of HVDC are

- Line losses are less
- In HVDC ground return can be used
- Transmission distance is not limited by stability
- Full control over power transmission

HVDC systems designed and operated so far are point to point systems with two terminals (converter stations) A multiterminal DC (MTDC) system has more than two converter stations with some of them operating as rectifiers and others ainverters In [2] it is mentioned that MTDC systems are more advantageous for certain applications such as

- Bulk power transmission from several remote generating stations to several load centers
- Asynchronous interconnection between adjacent power systems
- Saving of spinning reserve
- Reinforcement of a heavily loaded AC network by power injections at several points of the AC network

All these advantages make MTDC systems attractive though their control and protection involve complexities of much higher degree Also the reactive power consumption of the converter is about 60% of the real power to be transferred

Voltage stability study can be done using static V Q sensitivity analysis and static Q V modal analysis In V Q sensitivity analysis a voltage sensitivity factor [VSF] matrix is determined which relates the bus voltage magnitudes and bus reactive power injections

$$\Delta V = [VSF]\ \Delta Q$$

But V Q sensitivities cannot identify individual voltage collapse modes instead they provide information regarding the combined effects of all modes of voltage reactive power variation In Q V modal analysis the individual modal responses are isolated Participation of buses in the modes is identified Q V modal analysis is a convenient tool for voltage stability study and design of VAR compensation

1 4 Motivation for the Work

In reference [8] voltage stability study has been carried out for the reduced Northern Regional Grid of India (NRGI) system with just 15 buses (called NREB2 system in the study) This system is obtained after a two step reduction of the original NRGI system consisting of 357 buses NREB2 cannot be said to be realistically close to the original NRGI system Therefore it becomes necessary to carry out a detailed voltage stability study for a system that is much more realistic and closer to the original NRGI system in approximation The system used for study in the present work is a 111 bus system formed in [7] after one step reduction of the original 357 bus NRGI system This reduction is based on load flow considerations

Also in [8] the locations for placement of shunt compensation are determined only on the basis of major single line outages taking place in the system However it is necessary to examine the need for extra compensation taking into account any future growth in loads in the system

1 5 Objective of the Thesis

The objective of the thesis is to do a detailed voltage stability analysis of the reduced NRGI system using the methodology outlined in [8] Q V modal analysis and bus participation analysis is used to determine the buses/areas of the system that are prone to voltage instability problems and in need of shunt VAR compensation (fixed and / or dynamic) Continuation power flow analysis is done to study the effect of future increase in system loading levels on the overall system voltage stability

The system undertaken for case study is the Northern Regional Grid of India (NRGI) The NRGI consists of 357 AC buses 70 generators 1 HVDC link (bipole 1500 MW) and 1 SVC (2 units each of ±140 MVAR) with a total generation capacity of about 26 000 MW The present study has been done for the reduced NRGI system consisting of 111 AC buses 28 generators 1 HVDC link and 1 SVC (2 units each of ±140 MVAR) The objective is to analyze the system for the base case as well as for the major single line outages determine the critical line outages and then do detailed voltage stability analysis to identify the buses that are critical from the voltage stability point of view The present work also compares the following three alternatives used to enhance the voltage stability

1 Dynamic shunt compensation using SVCs
2 Strengthening of AC system with additional parallel lines
3 Series compensation of long lines

A further aim of the present work is to analyze effect of future system growth on its voltage stability using PFLOW [12] a software tool based on continuation power flow method and used for static voltage stability analysis The thesis examines effect of SVC voltage settings on voltage stability Furthermore adequacy of just one additional SVC placed at a judiciously chosen location for avoiding voltage collapse seen in recent times is also examined

1 6 Outline of Thesis

A chapter wise summary is as follows

- Chapter 2 looks into the MTDC AC system representation and linearization of system steady state equations Also a brief outline for the mathematical formulation of the voltage sensitivity matrix [VSF] is given Detailed mathematical formulation is given in [8]

- Chapter 3 deals with the methods useful for voltage stability analysis The two methods discussed are V Q sensitivity and Q V modal analysis Criterion of identifying critical buses from the bus participation factors is also discussed
- Chapter 4 covers the results and discussions
- Chapter 5 consists of conclusion and suggestion for further work

Chapter 2

Representation of MTDC-AC System for Voltage Stability Study

2 1 Introduction

The problem of voltage collapse in a power system is an important one and has been widely investigated in recent years While the disturbances leading to voltage collapse may be initiated by a variety of causes the underlying problem is an inherent weakness in the power system Load characteristics also have a major effect on voltage stability

There are two approaches to voltage stability analysis namely static analysis and dynamic analysis Static voltage stability analysis is done using algebraic equations defining the quasi steady state of the system Static analysis may not be strictly correct in some situations and system dynamics may need to be considered However in many situations static analysis is adequate Detailed voltage stability analysis with exhaustive dynamic modeling of the system components including the loads is a complex task

Voltage stability study can be done using static V Q sensitivity analysis [1 5] In V Q sensitivity analysis a voltage sensitivity factor [VSF] matrix is determined which relates the incremental change in bus voltage magnitudes to incremental change in bus reactive power injections

$$[\Delta V]= [VSF]\ [\Delta Q]$$

In the scalar case a positive V Q sensitivity indicates that the system is operating in a stable region If the V Q sensitivity is higher then the voltage is more sensitive to changes in reactive power injections and hence poorer voltage stability On the other hand a smaller and positive V Q sensitivity represents higher voltage stability If the V Q sensitivity is negative then the system is unstable [1]

In [5] voltage stability factor [VSF] matrix for a multi terminal HVDC (MTDC) system has been derived for different types of HVDC controls at the converters The VSF formulation has been done for the MTDC system with several of the AC systems connected to it having synchronous links between them

2 2 Representation of MTDC AC system

The major components of the MTDC AC system are synchronous generator AC/DC transmission line transformers converters (rectifiers and inverters) reactive power compensating devices (fixed compensation/dynamic compensation) loads etc The different characteristics of system components loads in particular effect the system voltage stability as well as overall stability in a major way For the formulation of [VSF] matrix proper representation of these components is required The steady state representation of these components is briefly discussed below

2 2 1 Generator Representation

The synchronous generator is represented simply as P-V bus operating within fixed reactive power limits However for exact analysis machine representation must include the field current limit armature current limit and under excitation limit

2 2 2 Load Representation

Load characteristics could be critical in voltage stability analysis Expanded sub transmission system representation including transformer ULTC action reactive power compensation and voltage regulators in a voltage weak area may be necessary It is important to account for voltage and frequency dependencies of loads As such proper load modeling has to be done This is not easy to do in practice In this thesis load has been modeled as constant PQ load which is the common practice

2 2 3 AC Transmission Line Representation

Nominal π model represents the AC transmission line The transformers connected in the lines are represented as fixed impedance in series with the line

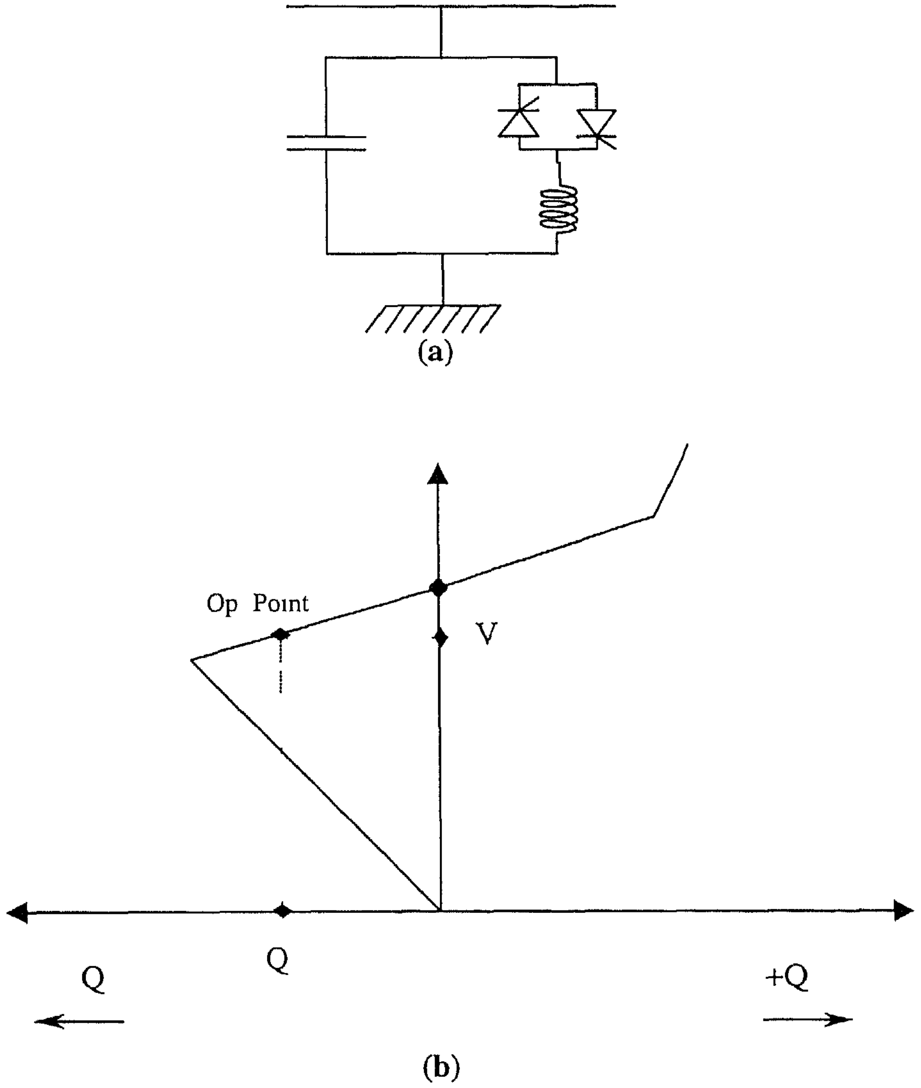
2 2 4 Static Var Compensator (SVC) Representation

The SVC is assumed to consist of a fixed capacitor connected in parallel with thyristor controlled reactor (TCR) The SVC operates in three regions with different steady state control characteristics responding to voltage change The SVC and its steady state characteristic is shown in Fig 2 1

Linear Control Region $Q = K\,(V_{ref} - V)$ $Q_{min} \leq Q \leq Q_{max}$

Constant Capacitance Region $Q = Y_{max}\,V^2$ $Q > Q_{max}$

Constant Inductance Region $Q = -\,Y_{min}\,V^2$ $Q < Q_{min}$



(a)

(b)

Fig 2 1 **Static Var Compensator and SVC Steady State Characteristics**

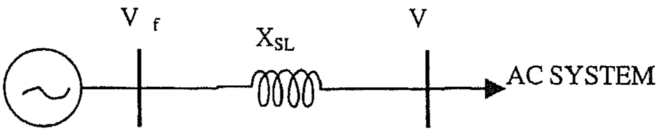


Fig 2 2 **SVC Model For Power Flow Studies**

The SVC model used for power flow studies has SVC represented as a fictitious generator in series with slope defining reactance X_{SL} as shown in Fig 2 2 The real power output of this generator is zero The reactive Q V characteristics in the different regions are used to derive [VSF] matrix appropriate to the operation of SVC

2 2 5 HVDC Transmission Line Representation

The HVDC transmission line is represented as a resistive line

2 2 6 Converter Representation

The converter connected to the AC bus is represented as constant PQ load as shown in Fig 2 2

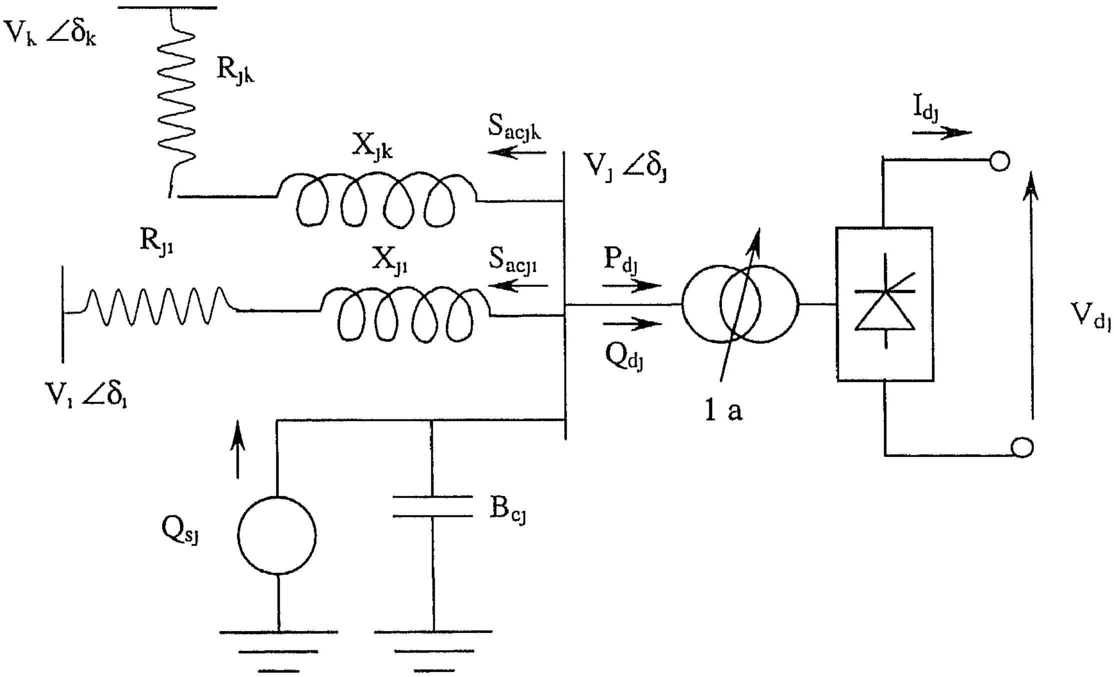


Fig 2 3 **Converter Terminal Connected to AC System Bus**

Converter equation

The pu DC voltage at the j^{th} terminal is given by

$$V_{dj} = k_j a_j V_j \cos\theta_j \pm R_{cj} I_{dj} \tag{2.1}$$

(+ for inverter – for rectifier)

where

I_{dj} is the pu DC current (+ for rectifier – for inverter)

V_j is the pu converter bus AC voltage

R_{cj} is the pu commutation resistance

k_j is a constant

a_j is the off nominal turns ratio of the converter transformer

θ_j is the delay angle (α_j) for rectifier or extinction angle (γ_j) for inverter

The expression for k_j and R_{cj} are given by

$$k_j = \frac{3\sqrt{2}n_j n_{ij} V_{bj}}{\pi V_{db}}$$

$$R_{cj} = \frac{3X_j n_{bj}}{\pi Z_{db}}$$

where

n_j is the nominal turns ratio of the converter transformer

n_{bj} is the number of bridges connected in series per pole

X_{cj} is the leakage reactance referred to the secondary side of the converter transformer in Ω

V_{acbj} is the base AC voltage

V_{db} is the base DC voltage

Z_{db} is the base DC impedance

The relation between the AC and DC system base quantities is given in Appendix A

The pu real and reactive power drawn by the j^{th} converter terminal are

$$P_{dj} = n_{pj} V_{dj} I_{dj} \tag{2 2}$$

$$Q_{lj} = \left|P_{lj}\right| \tan\phi_j \tag{2 3}$$

where

n_{pj} is the number of poles per converter terminal

The power factor at the j_{th} terminal is given by

$$\cos\phi_j = \frac{V_{dj}}{k_j a_j V_j} \tag{2 4}$$

The following assumptions are made for the computation of [VSF] matrix

1 The under load tap changers (ULTC s) of the converter transformer are slow in action and hence transformer taps are assumed to be constant during a transient

2 Any converter terminal can act as the voltage setting terminal

DC Network Equation

For an n terminal system if terminal m is chosen as the voltage setting terminal (VST) then the DC voltage at any terminal j is given by

$$V_{dj} = \sum_{k=1\, k\neq} (R_{jk} I_{dk}) + V_d \tag{2 5}$$

and the current at VST is given by

$$I_{ln} = -\sum_{k=1\, k\neq}^{i} (I_{dk}) \tag{2 6}$$

where R_{jk} is the jk^{th} element of DC bus resistance matrix [R] with DC bus m chosen as reference bus

For example for a two terminal system shown in Fig 2 3 if inverter is chosen as VST then

$$V_{dr} = R_d I_d + V_{di} \tag{2 7}$$

$$I_d = -I_i \tag{2 8}$$

where subscripts r and i represent rectifier and inverter respectively

Therefore

$$[R] = [R_d] \tag{2 9}$$

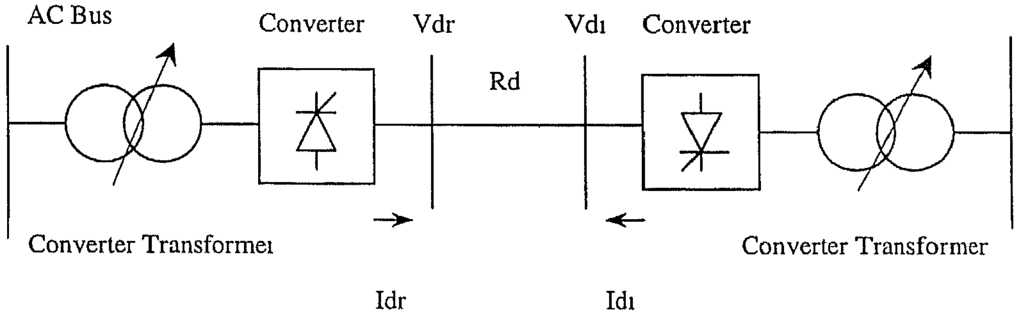


Fig 2 4 **Two Terminal DC System**

The real and reactive power equation at the converter bus can be written as

$$P_j = \frac{V_j \cos\theta_{zj} - V_j V_i \cos(\delta_j + \theta_{zj})}{Z_{ji}} + \frac{V_j \cos\theta_{zjk} - V_j V_k \cos(\delta_{jk} + \theta_{zjk})}{Z_{jk}}$$

$$= -P_{dj} \tag{2 10}$$

$$Q_{acj} = \frac{V_j^2 \sin\theta_{zji} - V_j V \sin(\delta_{ji} + \theta_{zji})}{Z_{ji}} + \frac{V_j^2 \sin\theta_{zjk} - V_j V_k \sin(\delta_{jk} + \theta_{zjk})}{Z_{jk}}$$

$$= -Q_{lj} + V_j^2 B_{cj} + Q_{vj} \tag{2 11}$$

where it has been assumed that bus j is connected to bus i and bus k only

Z_{ji} is the impedance of line between bus j and bus i

δ_j is the voltage angle of bus j

B_{cj} is the fixed shunt susceptance connected to bus j

Q_{sj} is the fixed reactive power injection at bus j

$$\delta_{j} = \delta - \delta_{j}$$

$$\tan\theta_{zj} = \frac{X_{ji}}{R_{j}}$$

$$Z_{j} = \sqrt{R_{j}^{2} + X_{j}^{2}}$$

DC Control Equation

The control strategy is to maintain each scheduled variable at a preset value The control equation at each terminal depends on the control strategy adopted and the type of the terminal it is Different control strategies are employed for the voltage setting terminal (VST) and the non voltage setting terminal (non VST)

At the non VST two types of controls can be adopted viz

- Constant DC Current Control
- Constant Power Control

Therefore at non voltage setting terminal j the scheduled variable is

$$W_{j} = I_{lj} \text{ or } W_{j} = P_{dj} \quad j = 1 \qquad n \quad j \neq m \tag{2 12}$$

where m represents VST

At VST the transformer tap is assumed to be constant Therefore any of the following control strategies can be used for VST [5]

- Constant angle (θ) control (delay angle α for rectifier or extinction angle γ for inverter)
- Constant reactive power (Q_d) control
- Constant reactive current (I_q) control
- Constant DC voltage (V_d) control

In practice the most commonly used control is either extinction angle control (VST is usually an inverter terminal) or DC voltage control So the scheduled quantity W_m at the voltage setting terminal (VST) is α_m or γ_m Q_{dn} I_{qi} V_{dn}

The reactive current I_{qm} is given by

$$I_{q\,i} = \frac{Q_d}{V} \tag{2 13}$$

2 3 VSF Matrix Formulation for MTDC AC System

The voltage sensitivity factor [VSF] matrix which relates the incremental change in bus voltage magnitudes to incremental change in bus reactive power injections is formulated for a MTDC AC system Q V modal analysis is carried out using the above formulated [VSF] matrix to determine the system voltage stability The detailed mathematical formulation of the [VSF] matrix for a MTDC AC system is given in [8] Same formulation is used in the present work as well Here only a brief outline of the steps involved in the mathematical formulation is presented

Linearizing the real power flow equations of the type given by equation (2 10) we get

$$[J_{P\delta}]\,[\Delta\delta] + [J_{PV}]\,[\Delta V] = -[\Delta P_l] \tag{2 14}$$

Linearizing the reactive power flow equations of the tvpe given by equation (2 11) we get

$$[J_{Q\delta}]\,[\Delta\delta] + [J_{QV}]\,[\Delta V] = -[\Delta Q_d] + [VB_c]\,[\Delta V] + [\Delta Q\ ] \tag{2 15}$$

In the above two equations

$[J_{P\delta}]$ $[J_{PV}]$ $[J_{Q\delta}]$ $[J_{QV}]$ are the jacobian matrices The equations for the non zero elements of the jacobian matrices are given in Appendix B In equation (2 14) and equation (2 15) besides the usual elements of the Jacobian matrices corresponding to the AC load flow problem there are additional terms related to the DC network embedded in the AC system

Therefore in order to establish a linear relationship between the incremental bus voltage magnitudes and corresponding bus reactive power injections linearization of the DC system equations is also done

The DC system linearization is done taking into account the type of HVDC converter (rectifier or inverter) and the different types of HVDC controls used at a particular converter terminal Linearization of the DC system results in a relationship of the form

$$\begin{aligned}[\Delta P_d] &= [J_{PVd}][\Delta V] \\ [\Delta Q_d] &= [J_{QVd}][\Delta V]\end{aligned} \qquad (2\ 16)$$

where

$[J_{PVd}]$ and $[J_{QVd}]$ are matrices similar to the Jacobian matrices for the AC load flow relating the change in real and reactive power injections at the converter terminals and change in the voltage magnitudes at the AC bus connected to the DC terminal

From equations (2 14) (2 15) and (2 16) we get

$$[\Delta Q] = [VSF]^{-1}[\Delta V] \qquad (2\ 17)$$

where

$[VSF]$ is the voltage sensitivity matrix giving a linear relationship between the bus voltage magnitudes and reactive power injections The voltage sensitivity matrix is modified to include the SVC characteristics as well The method used is given in [8]

Chapter 3

Voltage Stability Analysis

3 1 Introduction

Voltage instability is a problem most likely to be encountered in heavily stressed systems having inadequate reactive power support There have been a number of voltage collapse incidents worldwide [1] Based on these incidents voltage collapse may be characterized as follows

1 The process of voltage collapse can be initiated by a variety of causes such as small gradual system changes or large sudden disturbances like loss of major line or generating unit

2 The heart of the problem is the inability of the system to meet its reactive power demands Usually voltage instability involves system conditions with heavily loaded lines

3 The voltage collapse generally manifests itself as a slow decay of voltage involving actions and interactions of many devices controls and protective systems

4 Voltage instability is strongly influenced by system conditions and characteristics The significant contributing factors are as follows

  - Large distances between generation and load (inadequately compensated long transmission lines)
  - ULTC action during low voltage conditions
  - Unfavorable load characteristics
  - Poor coordination between various control and protective systems

In planning and operating power systems the analysis of voltage stability for a given system states involves the examination of two aspects

a) *Proximity* how close is the system to voltage instability?

b) *Mechanism* When voltage instability occurs what are the key contributing factors what are the voltage weak points and what are the areas involved?

Proximity gives a measure of voltage security whereas *mechanism* provides information useful in determining system modifications or operating strategies that could be used to prevent voltage instability

Voltage instability is indeed a dynamic phenomenon and can be studied using extended transient/midterm stability simulations However such simulations do not readily provide sensitivity information or degree of stability They are also time consuming Therefore application of dynamic simulations is limited to specific voltage collapse situations including fast or transient voltage collapse and for coordination of protection and controls

Since the system dynamics influencing voltage stability are usually slow many aspects of the problem can be analyzed by using static methods Voltage stability analysis often requires examination of a wide range of system conditions and a large number of contingency scenarios For such applications the approach based on steady state analysis can provide much insight into the voltage/reactive power problem

In the past the electric utility industry has largely depended on conventional power flow programs for static analysis of voltage stability Stability is determined by computing the V P and Q V curves at selected load buses A typical Q V curve is shown in Fig 3 1

On the right side of line AB increase in voltage is accompanied by an increase in reactive power injection This indicates a stable operating region for the system In the stable region dV/dQ is positive In the unstable region i e on the left side of line AB dV/dQ is negative At point C representing the critical point of stability dV/dQ is infinite

Executing a large number of power flows using conventional models generates the Q V curves This makes the entire process time consuming and also

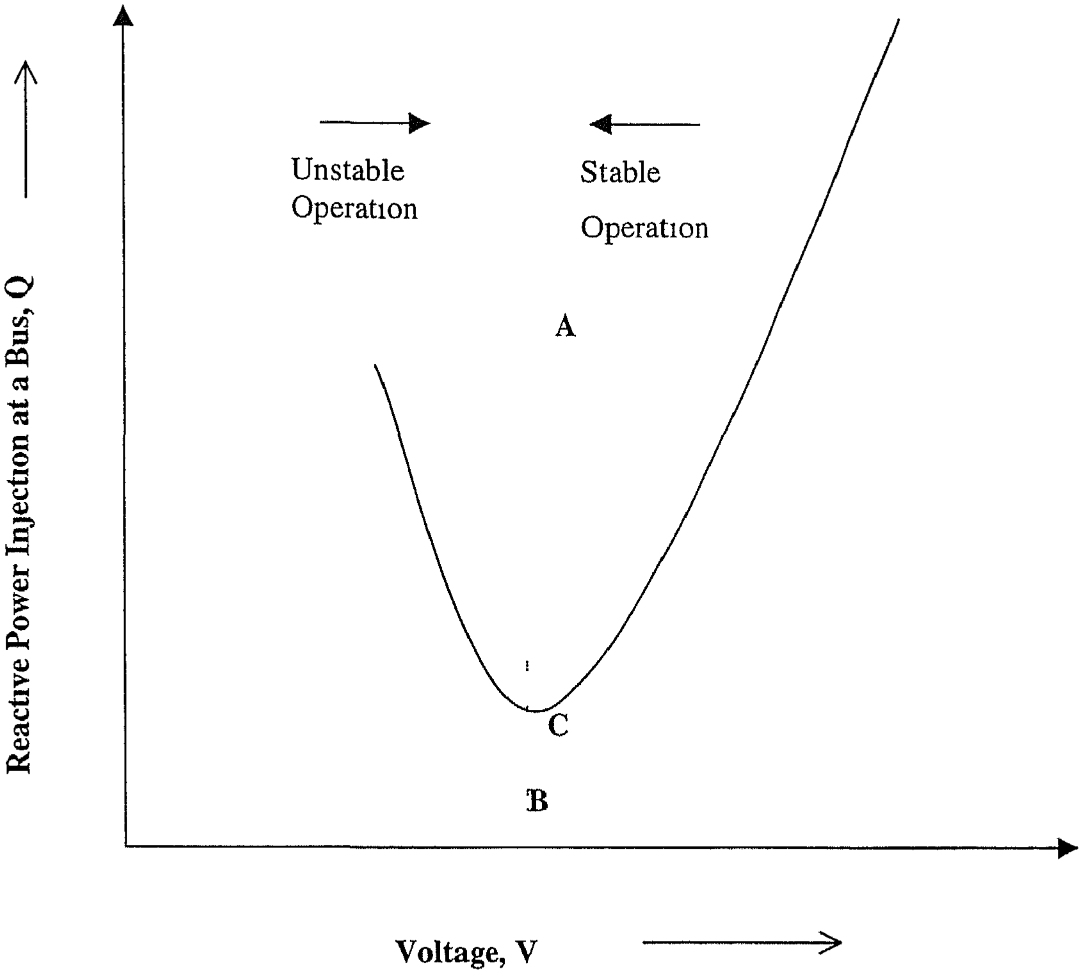


Figure 3 1 **Typical *Q V* curve at a Bus for Constant Active Power Loading of System**

the curves do not provide much insight into the causes of stability problems In addition these curves focus on the individual buses without taking into account the effect of VAR injections at the bus on the voltages of other buses For a large system generation of Q V curves becomes a cumbersome process

A number of special techniques have been proposed in the literature for voltage stability analysis using the static approach V-Q sensitivity analysis [1] and Q V modal analysis [4] are two such techniques These approaches give voltage stability related information from a system wide perspective and clearly identify areas that have potential problems The Q V modal analysis has the added advantage that it provides information regarding the mechanism of instability The modal analysis approach is able to give precise information regarding the location for placement of compensating devices including active devices such as SVCs

V Q sensitivity analysis is considered here as it serves as a good starting point to Q V modal analysis

3 2 V-Q Sensitivity Analysis

The steady state power flow equations can be represented as

$$P = f_1(\delta \; V)$$
$$Q = f_2(\delta \; V)$$

where P and Q are the active and reactive power injection vectors and δ and V are the bus voltage angles and voltage magnitudes vectors respectively

The linearized steady state system power flow equations are given by

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \qquad (3\ 1)$$

where

ΔP = incremental change in bus real power injection
ΔQ = incremental change in bus reactive power injection
$\Delta \delta$ = incremental change in bus voltage angle
ΔV = incremental change in bus voltage magnitude

If the conventional power flow model is used for voltage stability analysis the Jacobian matrix in Equation (3 1) is same as the load flow Jacobian of the system at the given operating point With enhanced device models included the elements of the Jacobian matrix are modified as explained in [8]

System voltage stability is affected by both P and Q However at each operating point we keep P constant and evaluate voltage stability by considering the incremental relationship between Q and V This is analogous to Q V curve approach Although incremental change in P are neglected in the formulation the effects of changes in system load or power transfer levels are taken into account by studying the incremental relationship between Q and V at different operating conditions

To reduce (3 1) let $\Delta P=0$ then

$$[\Delta Q]=[J_{QV}-J_{Q\delta}J_{P\delta}^{1}J_{PV}][\Delta V] \qquad (3\ 2)$$

or

$$[\Delta Q]=[J_R][\Delta V] \qquad (3\ 3)$$

where

$$[J_R]=[J_{QV}-J_{Q\delta}J_{P\delta}^{-1}J_{PV}] \qquad (3\ 4)$$

Then

$$[\Delta V]=[J_R]^{1}[\Delta Q] \qquad (3\ 5)$$

or

$$[\Delta V]=[VSF][\Delta Q] \qquad (3\ 6)$$

where

$[VSF]=[J_R]^{1}$ is the Voltage Sensitivity (Stability) Factor matrix

J_R is called the reduced Jacobian matrix of the system J_R directly relates the bus voltage magnitude and bus reactive power injection Eliminating the real power and angle part from the system steady state equations allows us to focus on the study of reactive demand and supply problem of the system as well as minimize computational effort

In reference [5] it is mentioned that a given system exhibits voltage stability if for all the system buses an increase in reactive power injection at a particular bus results in a corresponding increase in the bus voltage at that particular bus However if there is at least one bus in the system where an increase in reactive power injection results in a decrease in the bus voltage at that particular bus then the system exhibits voltage instability Alternatively a positive V Q sensitivity at all the system buses characterizes a voltage stable system If there is even a single bus having a negative V Q sensitivity the system is considered to be voltage unstable

The V Q sensitivity at a bus represents the slope of the Q V curve at the given operating point A positive V Q sensitivity (dV/dQ) is indicative of stable operation As stability decreases the magnitude of sensitivity increases becoming infinite (dQ/dV=0) at the stability limit Conversely a negative V Q sensitivity represents a very unstable operation Because of the non linear nature of the V Q relationships the magnitudes of the sensitivities for different system conditions do not provide a direct measure of the relative degree of stability The V Q sensitivities cannot identify individual voltage collapse modes instead they provide information regarding the combined effects of all modes of voltage-reactive power variations Hence Q V modal analysis with its capability of identifying individual bus participation in the critical modes becomes the preferred choice for static voltage stability studies

3 3 Q V Modal Analysis

Voltage stability characteristics of the system can be identified by computing the eigenvalues and eigenvectors of the reduced Jacobian matrix J_R Let the eigenvalues be assumed to be distinct

Then

$$[J_R] = [\xi][\Lambda][\eta] \qquad (3\ 7)$$

where

$[\xi]$ = right eigenvector matrix of J_R

$[\eta]$ = left eigenvector matrix of J_R

$[\Lambda]$ = diagonal eigenvalue matrix of J_R

The set of right and left eigenvector are assumed to be orthonormal i e

$$[\xi][\eta] = I$$

From equation (3 7)

$$[J_R]^{-1} = [\eta]^{-1}[\Lambda]^{-1}[\xi]^{-1} \qquad (3\ 8)$$

As $[\xi]^{-1} = [\eta]$ equation (3 8) becomes

$$[J_R]^{-1} = [\xi][\Lambda]^{-1}[\eta] \tag{3 9}$$

Substituting in equation (3 5) we get

$$[\Delta V] = [\xi][\Lambda]^{-1}[\eta][\Delta Q] \tag{3 10}$$

or

$$[\eta][\Delta V] = [\Lambda]^{-1}[\eta][\Delta Q] \tag{3 11}$$

The above equation may be written as

$$[\mathrm{v}] = [\Lambda]^{-1}[\mathrm{q}] \tag{3 12}$$

where

$[\mathrm{v}] = [\eta]\ [\Delta V]$ is the vector of modal voltage variations and

$[\mathrm{q}] = [\eta]\ [\Delta Q]$ is the vector of variation of modal reactive power injections

Equation (3 12) represents n decoupled modal equations Then for the i^{th} mode we have

$$\mathrm{v}_i = \frac{1}{\lambda_i}\mathrm{q} \tag{3 13}$$

Since we are dealing with decoupled scalar equations we can say from the arguments presented earlier about stability that if $\lambda_i>0$ the i^{th} modal voltage and corresponding modal reactive power vary in the same direction indicating the system is voltage stable If $\lambda_i<0$ the i^{th} modal voltage and the corresponding modal reactive power variations are along the opposite directions indicating the system is voltage unstable The magnitude of λ_i determines the degree of stability of the i^{th} modal voltage The smaller the value of λ_i the closer is the i^{th} modal voltage to being unstable If $\lambda_i = 0$ the i^{th} modal voltage collapses because any change in that modal reactive power causes infinite change in that modal voltage So for a system to be voltage stable all the eigenvalues of the reduced Jacobian matrix must be positive As the system is stressed the magnitude of at least one eigenvalue becomes small and at the critical point of loading the eigenvalue becomes zero

It has been shown in [4] that if the transmission network resistances are neglected and the bus admittance matrix Y_{BUS} is symmetrical the reduced Jacobian matrix J_R is also symmetrical Then the eigenvalues and eigenvectors of J_R are real In addition the right eigenvector and the left eigenvector of an eigenvalue of J_R are identical With phase shifting transformers (which make the matrix Y_{BUS} unsymmetrical) and line resistances J_R is only nearly symmetrical the eigenvalues of J_R for all practical purposes are real

3 4 Bus Participation Factors

The relative participation of bus k in mode i is given by the bus participation factor

$$P_{ki} = \xi_{ki}\eta_{k} \qquad (3\ 14)$$

P_{ki} determines contribution of λ_i in the V Q sensitivity at bus k

Bus participation factors determine the areas associated with each mode The sum of the bus participation factors for each mode is equal to unity because the right and left eigenvectors are normalized The size of the bus participation in a given mode indicates the effectiveness of remedial actions applied at the bus in stabilizing the mode With this information the buses or areas more prone to voltage instability can be identified

There are generally two types of modes The first type has very few buses with large participation indicating that the mode is very localized The second type has many buses with small but similar degrees of participations and all the other buses with close to zero participations indicating an non localized mode A typical localized mode occurs if a single load bus is connected to a strong network through a long transmission line A typical non localized mode occurs when a region within a large system is heavily loaded and the main reactive power support for this region is exhausted

It is impractical and unnecessary to calculate all the eigenvalues of the reduced Jacobian matrix J_R for a practical system with several thousand buses At the same time it is not advisable to consider only one eigenvalue of J_R because there is usually more than one weak mode associated with different parts of the system Also the mode associated with the minimum eigenvaule for the base case may not be the most troublesome mode as the system is stressed In fact there is every possibility of the initial non critical modes becoming critical once some system contingency takes place In practice 5 to 10 smallest eigenvalues are recommended to be computed to identify all critical modes [9]

Once the critical modes are identified the bus participation factors corresponding to the critical modes are determined using right and left eigenvectors Then the buses with higher bus participation factors for all critical modes are identified The higher the bus participation factor the more effective the bus in improving the critical modes

The ideal compensator should provide a controllable and variable amount of reactive power precisely according to the requirement and without delay If fixed amount of reactive power compensation is provided then for the worst case contingency operating point will be established But the stability margin would not be sufficient If instead of fixed reactive power compensation SVC is used and assuming that SVC is operating in control range for a worst case contingency the operating point will be established and at the same time voltage stability will also improve significantly This is because the effect of SVC on voltage stability is more compared to fixed reactive power compensation

3 5 Outlay of Analysis and Design

The following steps are involved in voltage stability analysis and compensation design

1 Integrated AC DC load flow study for the base case as well as with major single line outages (including outage of a DC pole)
Examination of line flows and voltage levels in the network

2 Determination of critical modes and buses showing major participation factors for the various cases considered above and for different DC line control strategies

3 Identification of areas and buses showing major participation in the critical modes Decision regarding buses to be used for shunt compensation

4 Determination of reactive power injections at the compensating buses in order to bring the bus voltages to set values (generally around 1 p u) for base case and contingencies For this study the existing SVC bus is represented as a P V bus (with P=0) and voltage set at the SVC voltage setting Shunt capacitor values are then determined for one critical area at a time to bring the bus voltages within the admissible range for base case and with contingencies VAR rating of capacitors is determined by doing repeated load flows with VAR injections determined earlier serving as guideline Improvement in critical modes is examined

5 If in an area fixed capacitors fail to achieve the required improvement in the bus voltages and associated critical modes SVCs are tried Ranges of SVCs are determined through integrated AC DC load flow for the base case and various identified contingencies considering the capacitors proposed for other areas to determine VAR injection requirement VSF matrix is formed for SVC slope of 3 % Critical modes are determined to assess improvement

6 The above outlined analysis is done to determine the buses which need shunt compensation (fixed or dynamic) with major single line outages being the governing factor behind the system voltage stability analysis However to put the things in right perspective continuation power flow analysis is done using PFLOW software tool [12] to study the effect of future system growth in terms of increased loads on the system voltage stability Any compensation in addition to the one determined using Q V modal analysis if needed is recommended

Chapter 4

Results and Discussions

4 1 System Description

The interconnected power systems of the states of Uttar Pradesh Jammu and Kashmir Rajasthan Haryana Himachal Pradesh and Delhi form the Northern Regional Grid of India (NRGI) The major generation in the system is thermal located at coal pitheads at Singrauli Rihand Anpara and Obra in the extreme southeastern part of the grid about 900 km from the major load centers in and around Delhi in the northwestern part Some generating stations are located close to load centers in the central and western part Hydro generation is located in the northern part in the Himalayan belt

NRGI consists of 357 AC buses 70 generators 1 HVDC link (bi pole 1500 MW) and 1 SVC (2 units each of ±140 MVAR) with a total generating capacity of about 26 000 MW The main transmission levels are 400 kV and 220 kV with 132 kV network providing radial connection to load centers Power transfer from the major generating area to the major load centers is over four major 400 kV lines and the HVDC line Voltage stability study is done on the reduced NRGI system consisting of 111 AC buses 28 generators 1 HVDC link (bi pole 1500 MW) and 1 SVC (2 units of ±140 MVAR) The system reduction is done on the following basis

- 400 kV and most of the 220 kV buses are retained
- 132 kV buses are replaced by appropriate loads
- Major generating stations are retained

- Effect of minor generations is included as loads i e as appropriate P Q injections

The reduced NRGI system data Grid map and single line diagram are given in Appendix C

The AC base voltage and AC/DC base power for the system are 400 kV and 100 MW respectively For voltage stability study different types of HVDC controls at the VST and non VST terminals are considered At the non VST two types of controls viz constant current (CC) and constant power (CP) are considered At the VST four different types of controls are taken into account

- Constant DC voltage (V_d) control
- Constant angle (θ) control (delay angle α for rectifier or extinction angle γ for inverter)
- Constant reactive current (I_q) control
- Constant reactive power (Q_d) control

4 2 Base Case System Analysis

Integrated AC DC load flow is done for the reduced NRGI system with one SVC at Kanpur to get the operating point It is found from the load flow results that the Kanpur SVC with a voltage setting of 1 p u is not floating under nominal operating conditions The Kanpur SVC supplies a reactive power of 157 2 MVAR This is not desirable and therefore to make the Kanpur SVC float under nominal operating condition a fixed shunt compensator of 157 2 MVAR is connected at bus 33 (Kanpur NTPC bus) For the analysis of the reduced NRGI system this forms the base case The load flow solution for the base case is given in Appendix D

For the base case Q V modal analysis of the NRGI system is done and eigenvalues of the [VSF]^{1} matrix are determined for different types of HVDC controls at the VST and non VST The eigenvalues for the base case are listed in Appendix E As expected all the eigenvalues of [VSF]^{1} are real This confirms with [4] Out of the total system eigenvalues (83 for the reduced NRGI system) only the dominant five eigenvalues (having magnitude close to zero) are considered for constituting the critical modes The dominant eigenvalues of the $[VSF]^{1}$ matrix for different HVDC controls at VST and non VST are given in Table 4 1

Table 4 1 **Base Case Critical Eigenvalues of $[VSF]^{1}$ matrix**

Mode	P_d Control at Non VST				I_d Control at Non VST			
	VST Controls				VST Controls			
	V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
A	6 33	6 23	6 20	6 18	6 33	6 18	6 14	6 17
B	7 38	7 33	7 32	7 31	7 38	7 31	7 30	7 31
C	8 45	8 42	8 41	8 40	8 44	8 39	8 38	8 39
D	9 38	9 38	9 38	9 38	9 38	9 38	9 38	9 38
E	9 23	9 23	9 23	9 23	9 23	9 23	9 23	9 23

Table 4 2 and Table 4 3 show the bus participation factors for critical modes for different types of HVDC controls at VST and non VST It is found that the modes corresponding to the critical eigenvalues and the participation factors for the buses participating in these critical modes are more or less the same for both P_d and I_d control at the non VST terminal

Tables 4 2 and 4 3 provide information about the buses showing the largest participation in the critical modes The critical buses basically belong to the Rajasthan (Bus 72 and Bus73) and the eastern Uttar Pradesh (Bus 35 and Bus36) regions of the NRGI system and therefore these two areas are identified as the ones most prone to voltage instability

There is however a basic difference the pattern of participation by the critical buses in the above mentioned areas The buses belonging to the Rajasthan region (Bus 72 and Bus 73) tend to show a localized participation in the critical modes i e a few buses in the region with relatively dominant participation factors Such localized participation may occur due to load buses at the end of long radial transmission lines If such localized modes are outside the region of major load centers they may be of little significance in the stability analysis Any stability problem in such regions is a localized one On the contrary the buses lying in the eastern U P region (Bus 35 and Bus 36) participate in the critical modes with similar participation factors These modes can therefore be termed as non localized modes with regard to the buses involved Also in this eastern U P region there could be several other buses with similar level of participation factors

Table 4.2 **Bus Participation Factors for Critical Modes**

(P_d Control at non VST)

BUS (Bus No)	**Mode A**				**Mode B**				**Mode C**				**Mode D**				**Mode E**			
	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q
AJAM GR 400 (35)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.07	0.09	0.08	0.08	0.09	0.10	0.09	0.10
MAU 400 (36)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.08	0.08	0.08	0.08	0.11	0.11	0.11	0.10
CHTRG 220 (72)	0.13	0.10	0.10	0.09	0.18	0.23	0.22	0.22	0.08	0.08	0.08	0.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NMBRA 220 (73)	0.13	0.10	0.10	0.09	0.19	0.23	0.22	0.22	0.09	0.09	0.09	0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4 3 **Bus Participation Factors for Critical Modes**

(I_d Control at non VST)

BUS (Bus No)	Mode A				Mode B				Mode C				Mode D				Mode E			
	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q	V_d	θ	Q_d	I_q
AJAM GR 400 (35)	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 07	0 07	0 07	0 07	0 09	0 09	0 10	0 10
MAU 400 (36)	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 08	0 08	0 08	0 08	0 11	0 11	0 11	0 11
CHTRG 220 (72)	0 13	0 10	0 09	0 09	0 19	0 2	0 23	0 23	0 06	0 08	0 07	0 06	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
NMBRA 220 (73)	0 13	0 09	0 08	0 09	0 19	0 23	0 23	0 23	0 06	0 07	0 07	0 06	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0

The instability of such a non localized mode generally involves a significant portion of the system If a mode contains a large number of buses the participation for each bus is generally small because the sum of all the bus participation factors is equal to unity The size of a bus participation factor in a given mode indicates the effectiveness of remedial action applied at that bus in stabilizing that particular mode

From the foregoing it can be concluded that for the eastern U P region due to lower values of individual bus participation factor use of dynamic shunt compensation at a single bus will not be that effective in improving system voltage stability Instead use of fixed shunt compensation at a number of buses in the region helps in improving the bus voltage profiles following some major contingency as well as contributes to improvement of system voltage stability by creating additional sources of reactive power in the system

Base case analysis points out Rajasthan and eastern U P as the two regions exhibiting proneness to voltage instability However in order to determine the exact locations for the placement of dynamic shunt compensation (SVC) it is necessary to carry out contingency analysis for major system line outages The reason being that in case of large systems there is every possibility that a non critical mode for the base case becomes one of the critical modes for a major system contingency This shifting of the critical modes may also lead to a change in the buses participating in the critical modes

4 3 Contingency Analysis

Contingency analysis is carried out for major single line outages in the system Eigenvalues of the [VSF] ^{1} matrix obtained for different outage conditions are examined to determine the critical contingencies having the worst effect on the system voltage stability The following major line outages are found to be the most critical and whose consideration is adequate for compensation design

1 Trunk Line 1 (TL1) Connecting Dadri 400 (Bus no 105) and Muradnagar 400 (Bus no 40) buses

2 Trunk Line 2 (TL2) Connecting Dadri 400 (Bus no 105) and Ballabhgarh

400 (Bus no 39) buses

3 Trunk Line 3 (TL3) Connecting Moradabad 400 (Bus no 44) and
Lucknow 400 (Bus no 34) buses

4 Trunk Line 4 (TL4) Connecting Muradnagar 400 (Bus no 40) and Panki
400 (Bus no 28) buses

At nominal operating condition power flows in TL1 TL2 TL3 and TL4 are 494 MW 317 MW 388 MW and 328 MW respectively The four dominant eigenvalues of [VSF] ^{1} matrix for outage of each trunk line with different HVDC controls at VST and non VST are given in Table 4 4

Table 4 4 **Dominant Eigenvalues of [VSF] ^{1} for Major Trunk Line Outages**

Outage	P_d Control at Non VST				I_d Control at Non VST			
	V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
TL1 Outage (40 105)	4 22	4 21	4 21	4 21	4 22	4 21	4 20	4 20
	6 80	6 70	6 70	6 65	6 80	6 71	6 68	6 70
	7 88	7 87	7 88	7 87	7 88	7 87	7 87	7 87
	9 22	9 21	9 21	9 21	9 22	9 21	9 21	9 21
TL2 Outage (39 105)	5 23	5 21	5 20	5 20	5 23	5 19	5 18	5 19
	7 82	7 81	7 80	7 80	7 82	7 81	7 80	7 81
	8 84	8 78	8 76	8 74	8 84	8 73	8 70	8 72
	9 18	9 17	9 17	9 17	9 18	9 17	9 16	9 17
TL3 Outage (44 34)	6 19	6 12	6 09	6 18	6 19	6 11	6 10	6 16
	7 14	7 11	7 09	7 14	7 14	7 10	7 09	7 14
	8 29	8 27	8 26	8 28	8 29	8 23	8 25	8 28
	9 23	9 23	9 23	9 23	9 23	9 21	9 23	9 23
TL4 Outage (40 28)	6 27	6 22	6 20	6 25	6 30	6 26	6 28	6 31
	7 31	7 26	7 28	7 32	7 35	7 31	7 33	7 35
	8 32	8 27	8 29	8 34	8 38	8 31	8 34	8 36
	9 24	9 23	9 23	9 24	9 27	9 24	9 25	9 27

From the voltage stability point of view TL1 (Dadri Muradnagar) and TL2 (Dadri Ballabhgarh) outages come out to be the worst It is also concluded from Table 4 4 that the outage of trunk lines TL3 and TL4 does not have much effect on the overall system voltage stability The magnitudes of the dominant eigenvalues of [VSF] ^{1} for TL3 and TL4 line outages are not much different from the corresponding base case values as shown in Table 4 1 However load flow results show that for all the line outages the voltage profiles at the buses lying in the eastern U P region are very poor Therefore fixed shunt compensation is provided at some selected buses lying in this region in order to improve the voltage profiles Table 4 5 gives the value of the fixed compensation (capacitve) at different buses The capacitor ratings are calculated for a bus voltage of 1 p u Voltage profiles at the buses with fixed shunt (capacitive) compensation incorporated for different operating conditions of the system (contingencies included) are given in Table 4 6

Table 4 5 **Fixed shunt compensation (capacitors)**

Sl No	**BUS (Bus No)**	**MVAR Rating (at 1 p u voltage)**
1	MAU 400 (36)	70 0
2	SLTN 220(41)	50 0
3	LUCK 400 (34)	50 0
4	PANKI 220 (45)	50 0

Table 4 6 **Voltages at Buses with Fixed Capacitors**

Bus No	**34**	**36**	**45**
Case	**V_{BUS}(p u)**	**V_{BUS}(p u)**	**V_{BUS}(p u)**
Base Case	0 986	0 984	0 988
TL1 Outage (40 105)	0 976	0 981	0 972
TL2 Outage (39 105)	0 982	0 979	0 976
TL3 Outage (34 44)	0 965	0 973	0 958
TL4 Outage (28 40)	0 967	0 980	0 964

From the foregoing analysis it can be said that the outage of TL1 and TL2 determine the locations for placement of dynamic shunt compensation (SVC) in the system Some additional alternatives are also looked into to improve system voltage profile

These include

- Strengthening of AC system with additional parallel lines
- Strengthening of AC system with series compensation of lines

A case wise analysis for the above compensation strategies is given in the following sections

4 4 Dynamic Shunt Compensation

The worst case line outages (TL1 and TL2) are used to determine the location for SVC placement in the system Detailed eigenvalue and participation factor analysis is done for the above two contingencies Critical modes corresponding to the critical eigenvalues listed in Table 4 4 and the corresponding buses showing largest participation in the critical modes are given in Table 4 7 and Table 4 8 for TL1 and TL2 outages respectively

Table 4 7 **Participation Factors & Critical Buses for Critical Modes (TL1 outage, fixed shunt compensation not incorporated)**

Control at VST	**P_d Control at Non VST**				**I_d Control at Non VST**			
	Eigen Value	**Mode**	**Part Factor**	**Bus No**	**Eigen Value**	**Mode**	**Part Factor**	**Bus No**
V_d	4 22	J	0 20 0 19	40 44	4 22	L	0 20 0 18	40 44
	6 80	M	0 08 0 07	72 73	6 80	M	0 08 0 06	72 73
	7 88	N	0 10 0 09	72 73	7 88	N	0 10 0 08	72 73
I_q	4 21	I	0 20 0 19	40 44	4 21	H	0 19 0 18	40 44
	6 70	J	0 08 0 07	72 73	6 71	J	0 08 0 07	72 73
	7 88	K	0 10 0 09	72 73	7 87	K	0 10 0 08	72 73
Q_d	4 21	I	0 19 0 18	40 44	4 20	I	0 19 0 18	40 44
	6 70	J	0 09 0 07	72 73	6 68	J	0 08 0 08	72 73
	7 87	K	0 10 0 09	72 73	7 87	K	0 10 0 09	72 73
θ	4 21	I	0 20 0 18	40 44	4 20	I	0 20 0 18	40 44
	6 65	J	0 08 0 08	72 73	6 70	J	0 08 0 07	72 73
	7 87	K	0 10 0 08	72 73	7 87	K	0 10 0 09	72 73

Table 4 8 **Participation Factors and Critical Buses for Critical Modes (TL2 outage, Fixed Shunt Compensation not incorporated)**

Control at VST	P_d Control at Non VST				I_d Control at Non VST			
	Eigen Value	Mode	Part Factor	Bus No	Eigen Value	Mode	Part Factor	Bus No
V_d	5 23	Q	0 10 0 10	55 62	5 23	Q	0 10 0 10	55 62
	7 82	R	0 07 0 06	72 73	7 82	R	0 07 0 06	72 73
	8 84	S	0 11 0 10	35 36	8 84	S	0 10 0 10	35 36
I_q	5 21	P	0 10 0 10	55 62	5 19	O	0 10 0 10	55 62
	7 81	Q	0 06 0 06	72 73	7 81	Q	0 07 0 07	72 73
	8 78	R	0 11 0 11	35 36	8 73	R	0 11 0 11	35 36
Q_l	5 20	P	0 10 0 09	55 62	5 18	O	0 10 0 09	55 62
	7 80	Q	0 07 0 07	72 73	7 80	Q	0 06 0 06	72 73
	8 76	R	0 11 0 11	35 36	8 70	R	0 11 0 11	35 36
θ	5 20	P	0 10 0 10	55 62	5 19	O	0 10 0 10	55 62
	7 80	Q	0 06 0 07	72 73	7 81	Q	0 07 0 06	72 73
	8 74	R	0 10 0 11	35 36	8 70	R	0 11 0 11	35 36

The participation factors for the buses participating in the critical modes for the worst case line outages give four possible locations for the placement of SVCs in the system These locations are

- ♦ Moradabad 400 (Bus no 44)—Muradnagar 400 (Bus no 40)
- ♦ Jaipur 400 (Bus no 62)—Jaipur 220 (Bus no 55)

Out of bus 44 and bus 40 bus 44 is chosen for placement of SVC This is so because Muradnagar Bus (40) being closer to Dadri generators is able to get reactive power support from them Also subsequent voltage collapse study brings out bus 44 as the preferable choice Out of bus 62 and bus 55 the former is chosen for SVC installation because it is the 400 kV network that is being analyzed from the voltage stability point of view

For the reduced NRGI system load flow analysis is conducted to get the operating point under nominal operating condition The fixed capacitive compensation designed earlier is also taken into account during the load flow analysis The voltage setting of all three SVCs (including SVCs at buses 44 and

62 and the existing SVC at Kanpur) is considered to be 1 p u It is found that SVCs do not float even under nominal operating conditions which is undesirable The reactive power supplied by the SVCs under different system operating conditions is given in Table 4 9 (a) and Table 4 9 (b)

Table 4 9 (a) **Bus Voltages and Reactive Power Support at SVC Buses for Base Case**

Case	Bus No	V_{BUS} (p u)	Q_{SVC} (MVAR)
Base Case	33	0 992	150 75
	44	0 999	3 06
	62	1 009	32 24

In order to make the SVCs float under nominal operating condition fixed shunt compensation of appropriate value (150 MVAR at bus 33 4 MVAR at bus 44 and –33 MVAR at bus 62) is provided This additional fixed shunt compensation enables the SVCs to utilize their entire control range during system contingencies Also Q V modal analysis shows that only additional fixed shunt compensation at the SVC buses does not contribute to voltage stability improvement in a significant manner Bus participation factors analysis shows that the buses identified as critical ones continue to participate in the modes corresponding to critical eigenvalues Thus installation of SVC is necessary in order to have a significant improvement in voltage stability of the system

To determine the exact ranges for the SVC s integrated AC DC load flow analysis is done for various systems operating conditions (major line outages) During the analysis the reactive power limits of the SVC buses are switched off and the fixed shunt compensation designed earlier is also taken into account Load flow analysis gives the reactive power supplied or absorbed by the SVCs as shown in Table 4 9 (b) The ranges for SVC operation as found from the load flow analysis are as follows

1 Moradabad 400 SVC +125 MVAR (capacitive) to –25 MVAR (inductive)
2 Jaipur 400 SVC +35 MVAR (capacitive) to –40 MVAR (inductive)

Table 4 9 (b) **Bus Voltages and Reactive Power Support at SVC Buses for the critical line outages (TL1 and TL2 outages)**

Case	Bus No.	V_{BUS} (p.u.)	Q_{SVC} (MVAR)
TL1 Outage (40-105)	33	0 991	186 81
	44	0 986	113 68
	62	1 010	-34 71
TL2 Outage (39-105)	33	0 993	127 40
	44	1 002	-17 60
	62	0 992	24 38

All the three SVCs operate with a slope of 3% With the three SVCs floating under nominal operating conditions Q-V modal analysis is done for the above system The dominant eigenvalues of $[VSF]^{-1}$ for different HVDC controls at VST and non-VST are given in Table 4 10

Table 4 10 **Dominant Eigenvalues of $[VSF]^{-1}$ with Proposed SVCs at Buses 44 and 62 (with fixed shunt compensation)**

P_d Control at Non-VST				I_d Control at Non-VST			
V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
7 52	7 47	7 46	7 45	7 52	7 46	7 45	7 46
8 34	8 34	8 33	8 33	8 34	8 33	8 33	8 33
9 23	9 22	9 22	9 22	9 23	9 22	9 22	9 22
9 36	9 35	9 35	9 35	9 36	9 34	9 34	9 34

Comparing eigenvalues in Table 4 10 with those in Table 4 1, it is observed that voltage stability of the system has improved But the improvement in the lowest eigenvalue is not significant

For the worst case line outages (TL1 and TL2), Q-V modal analysis is done with the two additional SVCs in the system Table 4 11 gives the dominant eigenvalues of the $[VSF]^{-1}$ for different HVDC controls at VST and non-VST. Comparing with the eigenvalues for the system without additional compensation, which are given in Table 4 4, it is observed that there is significant improvement in the lowest eigenvalues

Table 4 11 **Dominant Eigenvalues of $[VSF]^{-1}$ for TL1 and TL2 Line Outages with Proposed SVCs at Buses 44 and 62.**

Outage	P_d Control at Non-VST				I_d Control at Non-VST			
	V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
TL1 Outage (40-105)	7 45	7 38	7 36	7 34	7 45	7 37	7 35	7 37
	8 32	8 32	8 31	8 31	8 32	8 32	8 31	8 32
	9 02	9 01	9 01	9 01	9 02	9 01	9 01	9 01
	9 23	9 23	9 22	9 22	9 23	9 23	9 23	9 23
TL2 Outage (39-105)	7 35	7 32	7 32	7 31	7 35	7 32	7 31	7 32
	8 31	8 31	8 31	8 31	8 31	8 31	8 31	8 31
	9 23	9 22	9 22	9 22	9 23	9 22	9 22	9 22
	9 44	9 43	9 43	9 43	9 43	9 42	9 42	9 42

Furthermore it was found that buses which were participating in the most critical modes no longer come into the picture Therefore, it can be concluded that placement of the two additional SVCs of appropriate ratings definitely improves the overall system voltage stability following major line outages

In addition to the above-discussed contingencies, one DC pole outage of the HVDC line is also analyzed The present power setting of the HVDC line is 1000 MW From the eigenvalue analysis it is found that one DC pole outage is not as critical as the outage of a 400 kV trunk line running over a parallel path This is presumably because with DC pole outage, there are 4 AC trunk lines to take up the 500 MW flow, whereas, outage of an AC trunk line leaves only 3 trunk lines to take up a comparable flow The present study is limited to a DC flow of 1000 MW, which reflects the present DC line operating condition The above scenario may not hold when DC line carries its full rated power of 1500 MW Table 4 12 gives the dominant eigenvalues of $[VSF]^{-1}$ for one DC pole outage with different HVDC controls at VST and non-VST From the load flow analysis for one DC pole outage it is found that the Kanpur SVC hits its capacitive limit Placement of the two additional SVCs, as determined by the contingency analysis, relieves Kanpur SVC of supplying reactive power and allows it to operate within its control range

Table 4 12 **Dominant Eigenvalues of $[VSF]^{-1}$ for one DC Pole Outage**

P_d Control at Non-VST				I_d Control at Non-VST			
V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
6 46	6 38	6 36	6 36	6 46	6 34	6 32	6 34
7 86	7 86	7 86	7 86	7 86	7 86	7 86	7 86
8 72	8 70	8 70	8 72	8 72	8 69	8 68	8 68
9 24	9 24	9 24	9 24	9 24	9 24	9 24	9 24

Table 4 13 **Dominant Eigenvalues of $[VSF]^{-1}$ for one DC Pole Outage with Additional SVCs at Buses 44 and 62.**

P_d Control at Non-VST				I_d Control at Non-VST			
V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
7 05	7 05	7 04	7 05	7 05	7 05	7 04	7 05
7 55	7 53	7 51	7 52	7 55	7 55	7 53	7 54
9 08	9 07	9 04	9 08	9 08	9 07	9 04	9 05
9 24	9 24	9 24	9 24	9 24	9 24	9 24	9 24

4.5 Strengthening of System with Additional Parallel Lines

Incorporation of additional parallel lines in the existing system increases the system strength This is expected not only to increase the power transfer capability of the system, but also system voltage stability We will restrict our attention to having additional lines parallel to the trunk lines only Here, we will consider the following four cases

Case 1. Additional line parallel to each trunk line ,i e , addition of 4 parallel lines

Case 2 Additional parallel lines between buses Muradnagar 400 and Panki 400 and Moradabad 400 and Lucknow 400 with outage of line between buses Dadri 400 and Muradnagar 400

Case3 Additional line parallel to the line between buses Muradnagar 400 and Panki 400 with outage of line between buses Muradabad 400 and Lucknow 400

Case4 Additional line parallel to the line between buses Kanpur 400 and Ballabhgarh 400 with outage of the line between buses Dadri 400 and Ballabhgarh 400

Table 4 14 gives the dominant eigenvalues of $[VSF]^{-1}$ for different HVDC controls at VST and non-VST with additional parallel lines present in the system Now we will discuss each case briefly

Case 1 When there is additional parallel line for each trunk line, then load flow solution shows that inductive limit of Kanpur SVC is violated For load flow solution if inductive limit of Kanpur SVC is opened, then reactive power supplied by SVC comes out to be –331 7 MVAR The effect of three additional parallel lines is to drive Kanpur SVC to its inductive limit saturation Under this condition, compared to base case, instead of improving ,voltage stability deteriorates

Table 4 14 **Dominant Eigenvalues of $[VSF]^{-1}$ with Additional Parallel Line**

Case	P_d Control at non-VST				I_d Control at non-VST			
	V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
Case 1	6 12	5 98	6 00	6 11	6 12	5 94	5 97	6 10
	7 23	6 67	6 88	7 16	7 23	6 65	6 96	7 14
	8 10	7 83	7 95	8 04	8 10	7 94	8 00	8 07
	9 05	9 02	9 02	9 05	9 06	9 04	9 03	9 05
Case 2	6 42	6 35	6 33	6 32	6 42	6 34	6 31	6 33
	7 23	7 23	7 23	7 23	7 23	7 23	7 23	7 23
	7 45	7 41	7 40	7 40	7 46	7 42	7 42	7 42
	8 95	8 92	8 92	8 91	8 95	8 93	8 93	8 92
Case 3	6 61	6 49	6 46	6 44	6 61	6 45	6 41	6 45
	7 88	7 88	7 87	7 87	7 88	7 88	7 88	7 88
	8 61	8 61	8 60	8 60	8 61	8 60	8 60	8 60
	9 21	9 20	9 20	9 20	9 21	9 20	9 20	9 20
Case 4	6 01	5 98	5 98	5 97	6 01	5 97	5 96	5 97
	7 88	7 86	7 85	7 85	7 88	7 86	7 86	7 86
	9 00	8 94	8 92	8 91	9 00	8 90	8 88	8 90
	9 24	9 23	9 23	9 24	9 24	9 23	9 23	9 23

Case 2 This is the case corresponding to TL1 outage with additional parallel lines present in the system Comparing the eigenvalues given in Table 4 12 with the ones for an uncompensated system, it is observed that there is some improvement

in the lowest eigenvalue However, improvement in the system voltage stability is more when dynamic shunt compensation is used

Case3 For this case there is only a slight improvement in the system voltage stability However, the Kanpur SVC operates within its control range

Case 4 This case corresponds to the TL2 outage Again a comparison of the eigenvalues of Table 4 12 and Table 4 4 shows that there is not any significant improvement in the system voltage stability Dynamic shunt compensation again proves to be a more effective means of improving the system voltage stability

4.6 Strengthening of System by Series Compensation of Lines

Series compensation (about 35%-40%) of some of the lines increases the strength of the system Here, 35% series compensation of trunk lines is considered The following three cases are considered for voltage stability study

Case 1 All trunk lines are 35% series compensated

Case 2 Dadri-Muradnagar 400 kV line outage with 35 % series compensation of Muradnagar-Panki 400 kV and Moradabad-Lucknow 400 kV lines

Case 3 Dadri-Ballabhgarh 400 kV line outage with 35 % series compensation of Kanpur-Ballabhgarh 400 kV line

Table 4 15 shows the dominant eigenvlaues of $[VSF]^{-1}$ for different types of HVDC controls at VST and non-VST with series compensation of lines

Now we will discuss each case briefly

Case 1 Comparing the eigenvalues for this case with those given in Table 4 1 it is seen that the improvement in voltage stability is not significant So for nominal case series compensation is not a preferable alternative to improve voltage stability

Case 2 This case corresponds to the TL1 outage analysis done in section 4 4 Comparing the eigenvalues with those given in Table 4 4 and Table 4 11, it is observed that series compensation of the trunk lines results in a slight improvement in the system voltage stability, but the use of dynamic shunt compensation is much more effective

Case3 This case corresponds to the TL2 outage analysis done in section 4 4 Comparing the eigenvalues with those given in Table 4 4 it is seen that there is very little improvement in system voltage stability Hence, it can be said that series compensation of lines is not a preferable alternative in this case

Table 4 15· **Dominant Eigenvalues of $[VSF]^{-1}$ for Series Compensation of Lines**

Case	P_d Control at non-VST				I_d Control at non-VST			
	V_d	I_q	Q_d	θ	V_d	I_q	Q_d	θ
Case 1	6 45	6 38	6 36	6 35	6 45	6 36	5 97	6 35
	7 43	7 38	7 36	7 36	7 43	7 36	7 35	7 36
	8 58	8 55	8 54	8 53	8 58	8 53	8 51	8 52
	9 26	9 26	9 26	9 26	9 26	9 26	9 26	9 26
Case 2	5 97	5 94	5 93	5 93	5 97	5 92	5 91	5 92
	6 66	6 63	6 62	6 62	6 66	6 64	6 64	6 64
	7 44	7 39	7 38	7 37	7 44	7 39	7 38	7 39
	8 89	8 87	8 86	8 86	8 89	8 87	8 86	8 87
Case 3	5 70	5 68	5 67	5 67	5 70	5 66	5 65	5 66
	7 82	7 80	7 80	7 79	7 82	7 80	7 80	7 80
	8 96	8 90	8 88	8 87	8 96	8 86	8 83	8 85
	9 21	9 21	9 21	9 20	9 21	9 20	9 20	9 20

4 7 Continuation Power Flow Analysis

The voltage stability analysis done in the previous sections to determine the locations for fixed and dynamic shunt compensation was based on analysis of major single line outages, including one DC pole outage However, to put the things in the right perspective it becomes necessary to look at the voltage stability problem from the point of view of system planning for future growth as well

While the magnitude of eigenvalues, obtained from Q-V modal analysis, can provide a relative measure of the proximity to instability, they do not provide an absolute measure It is only in the region close to the voltage stability limit that the eigenvalues show appreciable deviations Continuation power flow comes out as a preferable choice to determine the megawatt distance to voltage stability

The NRGI system being studied is a highly developed system having more or less fixed generating capabilities but continuously increasing system loads

Therefore, it becomes necessary to determine the amount by which the present system loading levels and the corresponding generations can be increased without jeopardizing system voltage stability PFLOW software is used to determine the static voltage stability limit of the system This software uses the continuation power flow method to determine the system operating points in the voltage stable as well as unstable regions A brief description of the continuation power flow method and the PFLOW software is given below

4.7.1 PFLOW software [12]

PFLOW is a research tool that has been designed to calculate bifurcation characterized by singularity of the power system Jacobian This was developed based on the continuation power flow method The system Jacobian matrix becomes singular at the voltage stability limit Consequently, conventional power-flow algorithms are prone to convergence problems at operating conditions near the stability limit The continuation power flow analysis overcomes this problem by reformulating the power equations so that they remain well-conditioned at all possible loading conditions

The PFLOW program reads ac power flow data in different formats However, in the present study EPRI format data was used

4.7.2 System Study for Future Growth using PFLOW

Static voltage stability analysis was done with the system loads increased simultaneously by a factor of λ, called system loading factor (a constant factor by which the system loading levels are increased in steps up to the maximum possible loading) Zero load factor corresponds to the base case intact system condition An equivalent increase in the system generation is done Both, uncompensated system and system with additional fixed and dynamic shunt compensation are analyzed Figures 4 1 to 4 4 show the voltage profiles at the buses that experience maximum change in voltages with an increase in the system-loading factor λ From the figures it is clear that the system, in absence of any additional compensation, is operating rather close to the its voltage stability limit and an increase of about 12 % in the system loading from its base value makes it voltage unstable Also providing fixed and dynamic shunt compensation at the buses identified from the contingency analysis results in an insignificant improvement in the system stability margin (from 12% to 15% only)

The buses that were identified as critical lie in the eastern U P region of the system These include Lucknow 400 (Bus no 34), Panki 400 (Bus no 45),Mau400 (Bus no 36), Sultanpur 400 (Bus no 32) and Ajamgarh 400 (Bus no 35) It was recommended in Section 4 3 that fixed shunt compensation should be provided in this region, as it is inherently deficient in reactive power

However, the continuation power flow analysis shows that this additional compensation is not sufficient to improve the system voltage stability margin The PFLOW software [12] gives the ranking of weak buses at the collapse point and corresponding absolute values of the eigenvector elements associated with the smallest Jacobian eigenvalues

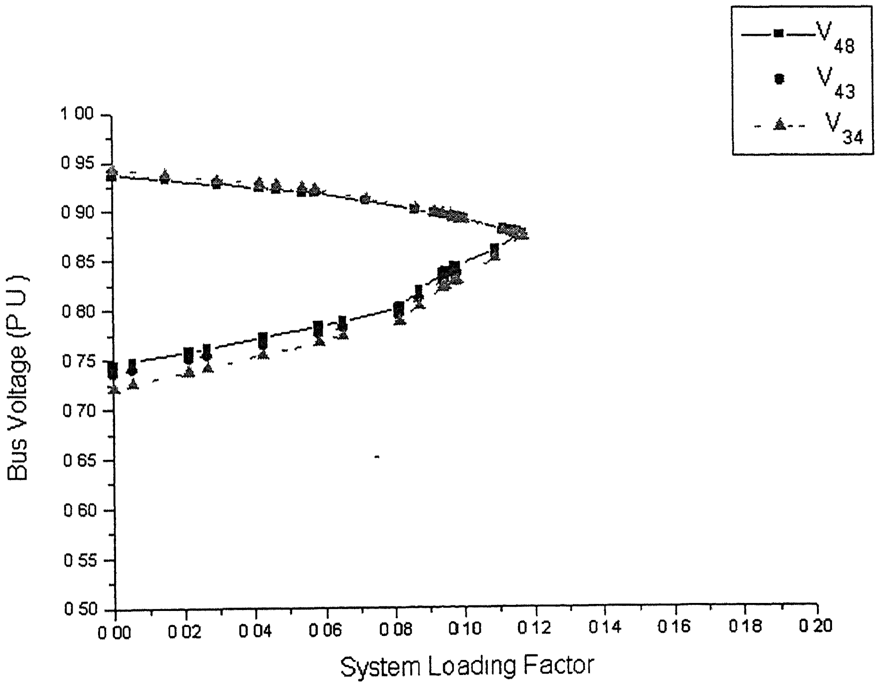


Fig 4 1 **Voltage profile at Critical Buses for Uncompensated System**

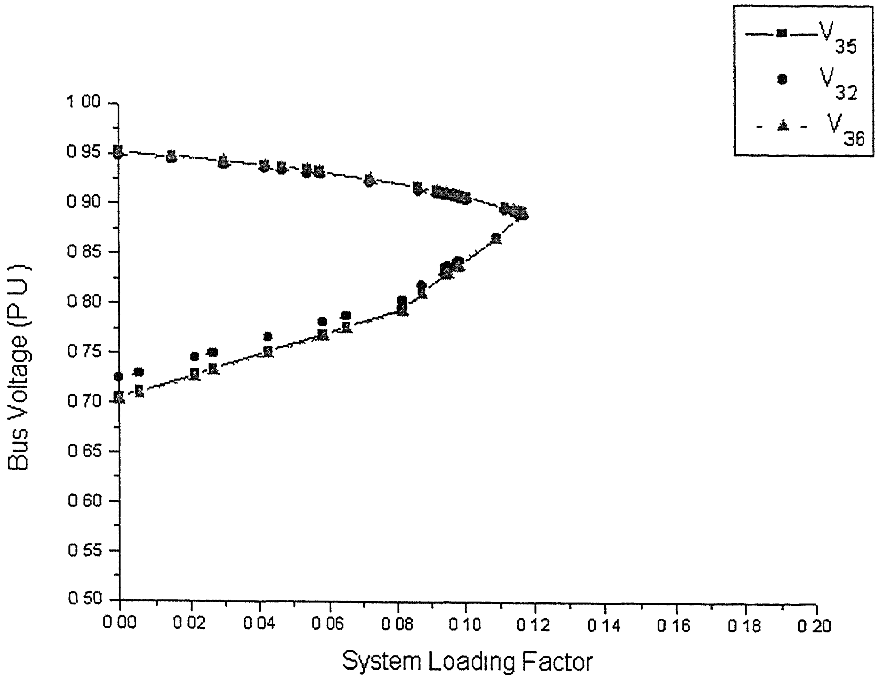


Fig 4 2 **Voltage Profiles at Critical Buses for Uncompensated System.**

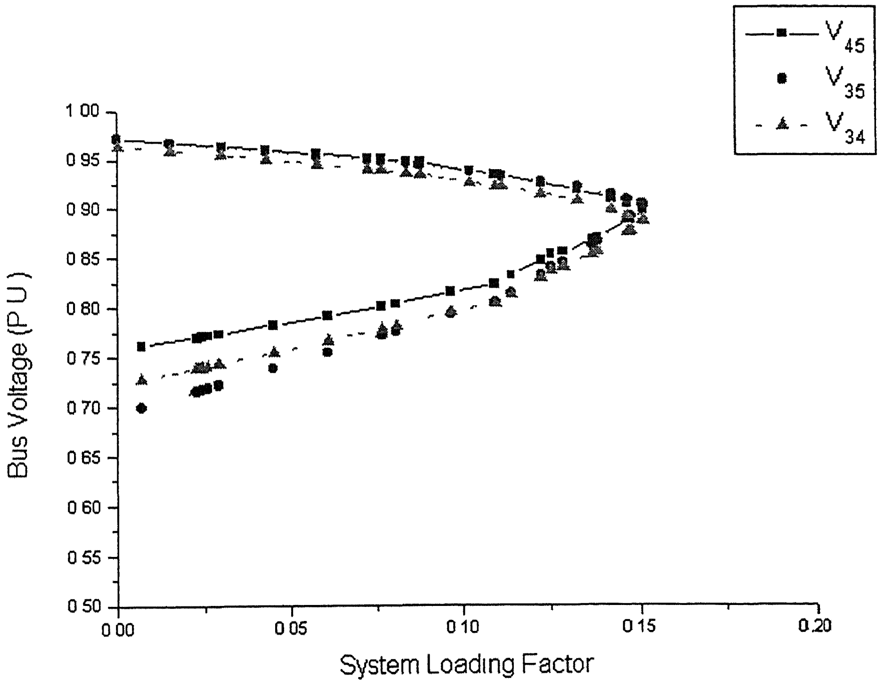


Fig 4 3 **Voltage Profiles at Critical Buses with additional Compensation(SVC at Bus 44 and Bus 62).**

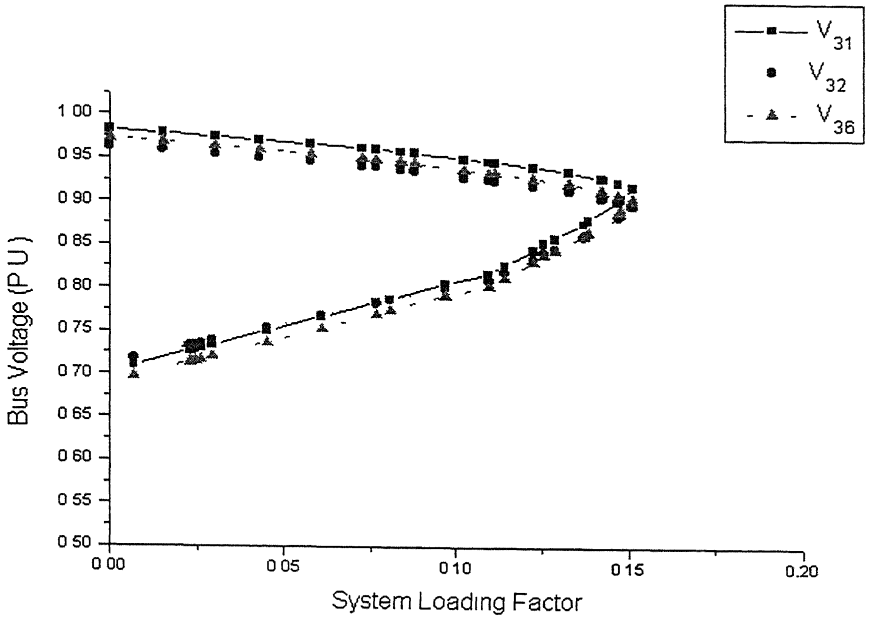


Fig 4 4 **Voltage Profiles at Critical Buses with additional Compensation (SVC at Bus 44 and Bus 62).**

Table 4 16 shows the ranking of weak buses at the point of collapse and the corresponding eigenvectors Two possible locations for additional shunt compensation are,

1 Lucknow 400 (Bus no 34)

1 Panki 220 (Bus no 45)

Table 4 16 **Weak Buses at the Collapse point for the NRGI system**

Ranking	Bus no	Bus Name	lRight eigenvectorl
1	34	LCK400	1
2	45	PANKI220	0 78342
3	36	MAU400	0 73861
4	32	SLTN400	0 71167
5	35	AJAMGR400	0 70582

Therefore, it can be concluded that only two additional SVCs at buses 44 and 62 are sufficient to maintain system voltage stability following any major single line outage However, more additional shunt compensation is needed at buses 34 and 45 to improve the system voltage stability margin in order to accommodate any future load increase in the system

4.8 Voltage Collapse Study

An analysis of the past history of grid collapse in the NRGI system, specially the November 1996 episode, reveals that a critical factor responsible for the collapse has been the outage of one of the HVDC poles This has generally resulted in a poor voltage profile at several critical buses in the system Any subsequent contingency has a cascaded effect resulting in grid collapse due to above low voltages It has also been noticed that in these incidents, the generators near load centers were not deployed to provide sufficient reactive power support due to practical constraints

A DC pole outage study is performed on the reduced NRGI system with and without an additional SVC at Moradabad as was done in [7] The contention here is that, apart from the existing SVC at Kanpur, just an additional SVC at Moradabad of sufficient capacity will help in avoiding grid collapse of the kind encountered earlier The effect of different SVC voltage settings on the system stability is also investigated

The variation of Dadri bus voltage with reactive power contribution from Dadri generator during healthy system operation (base case) and one DC pole outage without additional SVC is shown in Fig 4 5 It is to be noted that the VAR compensation and filters corresponding to the DC pole remain in circuit though the pole has been shut down

From Fig 4 5 it is clear that for a reactive power support of less than 220 MVAR from the Dadri generator, voltage collapse takes place In practice Dadri generators are not able to provide the above reactive power because of operating constraints For one DC pole outage condition the Kanpur SVC hits the capacitive limit when reactive power support is less than 220 MVAR In order to avoid a voltage collapse scenario reactive power support has to be provided from other avenues One possible solution for alleviating the reactive power deficit at Dadri is to provide one additional SVC in the nearby region

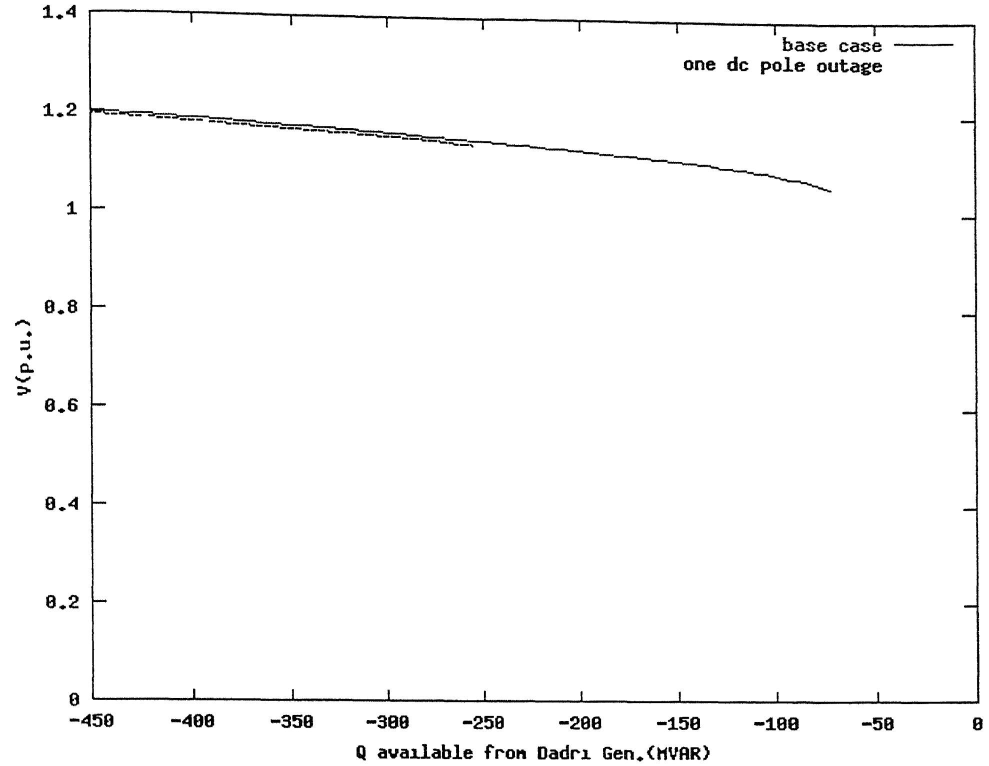


Fig 4 5 **Dadri Generator Bus Voltage Profile without Additional SVC (load flow does not converge beyond the curve drawn)**

One possible option, investigated in the present study is use of a SVC at Moradabad 400 bus The rating of the SVC is taken to be the same as determined from the contingency analysis done in Section 4 4, i e, +125 MVAR to –25 MVAR

Fig 4 6 shows the variation of Dadri generator bus voltage with additional reactive power support provided by the Moradabad SVC The voltage settings for both the SVCs are 1 0 p u It is clear from the figure that for a reactive power support of 200 MVAR from the Dadri generator the system has still enough stability margin In fact use of the extra SVC allows stable system operation even when Dadri generator is providing reactive power support of only around 120 MVAR for one DC pole outage

This may be the simplest solution capable of fast implementation for avoiding collapses of the NRGI system of the type which have occurred in the recent past For one DC pole outage condition, the Kanpur SVC hits the capacitive limit even though the reactive power support from Dadri generator is around 250 MVAR The same thing happens with the Dadri generator supplying around 100 MVAR with additional SVC operating at Moradabad

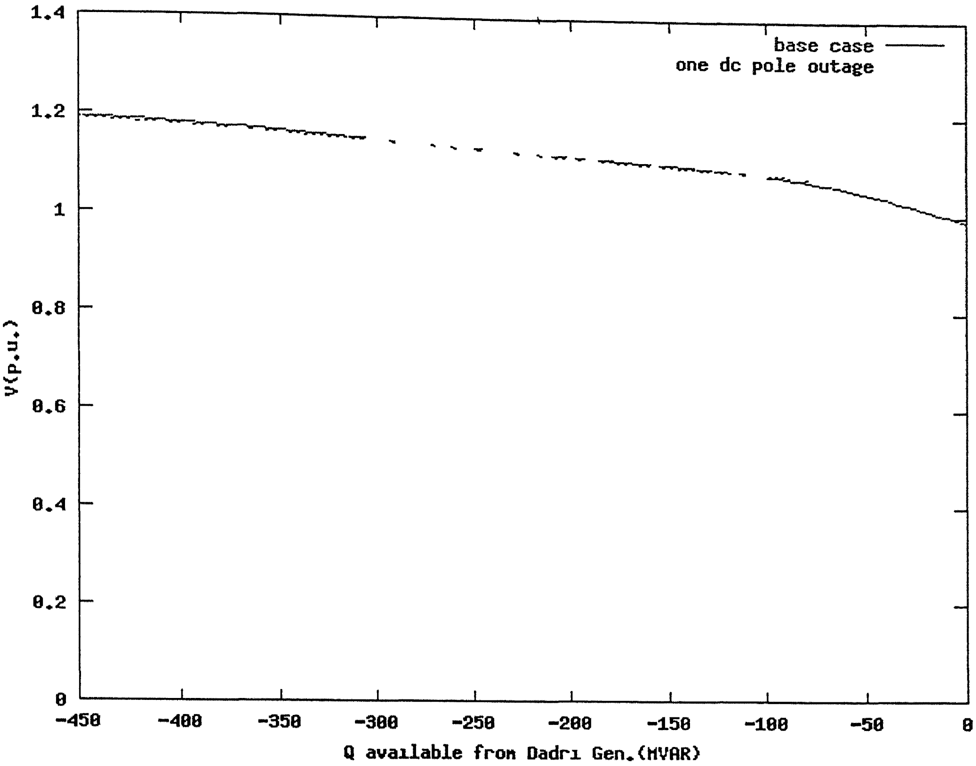


Fig 4 6 **Dadri Generator Bus Voltage Profile With Additional SVC at Moradabad**

To avoid Kanpur SVC from hitting its capacitive limit time and again, a change in the voltage settings of the SVCs is done The voltage settings of the Kanpur and Moradabad SVC are changed from 1 0 p u to 1 0116 p u and 1 022 p u respectively These values of voltages are obtained from the load flow solution of the reduced NRGI system without Kanpur SVC The variation of Dadri bus voltage with reactive power contribution from Dadri generator with one DC pole outage for two different voltage settings of voltage of Kanpur SVC is shown in Fig 4 7 Here no additional SVC is present

With increased voltage setting of SVC it is found that system will survive the single DC pole outage with a reasonable margin if Dadri generator supplies about 100 MVAR compared to the 220 MVAR it has to supply when SVC is operated at a setting of 1 p u However, without use of additional SVC at Moradabad the Kanpur SVC again hits its capacitive limit

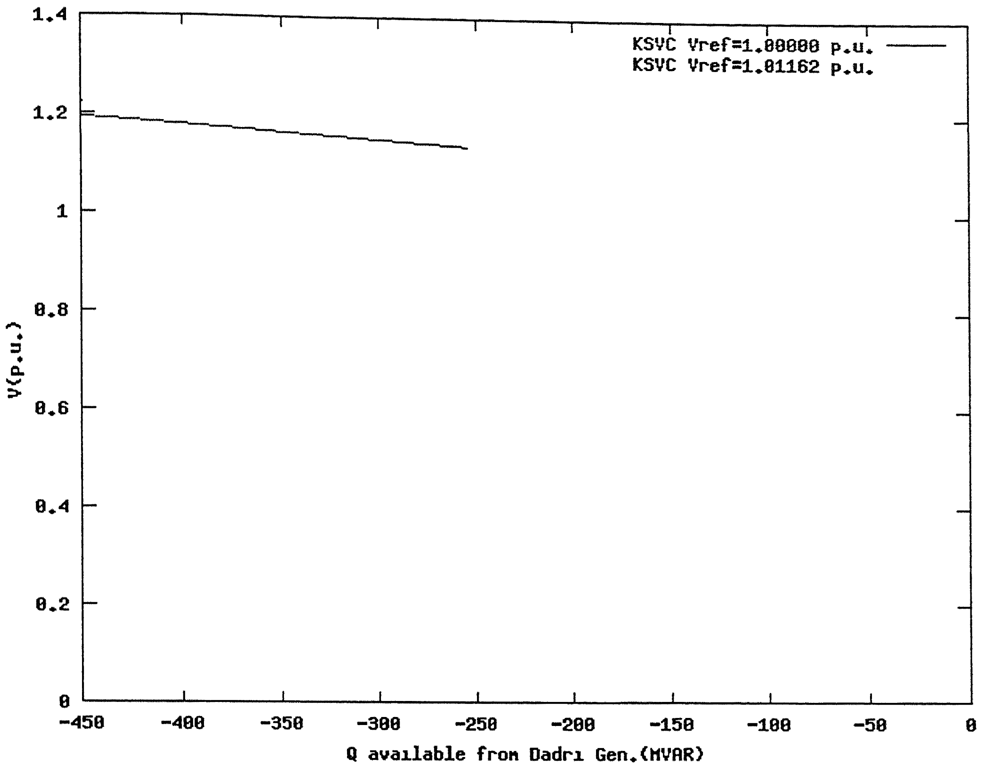


Fig 4 7 **Dadri Generator Bus Voltage Profile With Kanpur SVC operaed at Two Different Voltage Settings**

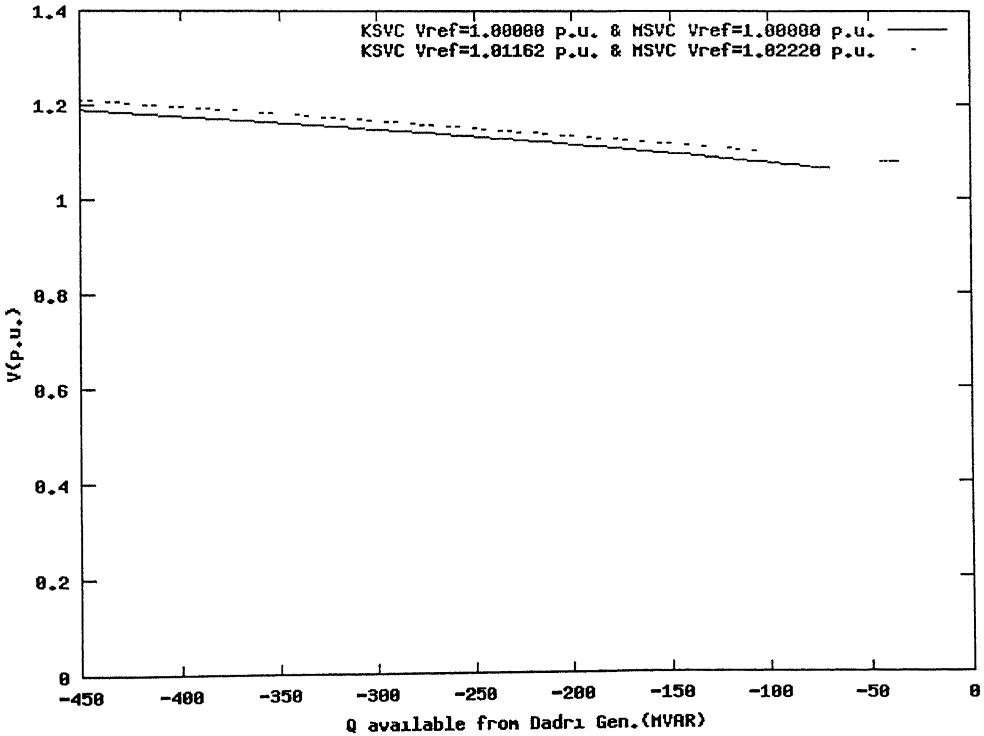


Fig 4 8 **Dadri Generator Bus Voltage Profile with Kanpur and Moradabad SVCs at two Different Voltage Settings**

Fig 4 8 shows the Dadri bus voltage profile for single DC pole outage, with two SVCs at the changed voltage settings installed in the system With the capacitive limit and operates within its control range Also the reactive power support needed from the Dadri generator to have a stable system operation is only about 20 MVAR in this case Therefore, it can be concluded that the position as well as the voltage settings of SVC influences the voltage stability of the system

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Chapter 5

Conclusion and Suggestions for Further Work

5.1 Conclusion

- Modal analysis of the reduced NRGI system, considering major single line outages, gives Moradabad 400 and Jaipur 400 buses as the locations for placement of dynamic shunt compensation. Modal analysis and bus participation factor analysis show that with the above compensation installed there is significant improvement in the magnitudes of critical eigenvalues obtained following critical line outages. Also buses participating in the critical modes for the uncompensated system no longer come into the picture.
- Continuation power flow analysis shows that the system is operating rather close to instability (a margin of only 12% - 15% increases in system loading levels available). Also, two new SVCs need to be installed at Lucknow 400 and Panki 220 in addition to the two SVCs determined from contingency analysis, to avoid any system collapse following any sort of future system expansion.
- It has been shown that voltage collapse of the kind encountered in the recent times in the NRGI system can be avoided by just one additional SVC of –25/+125 MVAR (generator sense) rating placed at Moradabad 400 kV bus.
- It is also concluded that voltage settings of SVC have a major effect on the voltage collapse of the system.

5.2 Suggestions for Further Work

- The present study uses steady state models of power system components for voltage stability analysis without going into their detailed modeling However, like the SVC limits generator armature current limit, field current limits and under excitation limit can be included in generator representation These limits may be incorporated in future work Since voltage dependency of load real and reactive power may have large impact on system voltage stability, detailed load modeling will be a good idea
- The Q-V modal analysis used for voltage stability analysis does not give an exact idea of the nearness of the system to voltage instability It is very difficult to say from the magnitudes of the eigenvalues that how far is the system from the point of instability Further system studies can be carried out using some other static or dynamic voltage stability analysis tools to determine the proximity indicators to voltage stability limit
- Present study is confined to use of SVC as a means for improving system voltage stability Further work can be done to study the use of other FACTS devices such as TCSC, UPFC, STATCON etc as means of improving the system voltage stability

Appendix A

AC and DC System Base Quantities

AC System

P_{acb} = AC system base MVA (MW) = 100 00

V_{acb} =AC system base voltage (L-L, kV) = 400 00

I_{acb} =AC system base current (kA)

$$I_{acb} = \frac{(P_{ac})}{\sqrt{3}V_{acb}}$$

DC System

P_{db} =DC system base power (MW) = P_{acb}

V_{db} =DC system base voltage (kV)

$$V_{db} = \frac{3\sqrt{2}V_{acb}}{\pi}$$

I_{db} =DC system base current (kA)

$$I_{db} = \frac{P_{db}}{V_{db}}$$

Appendix B

System Jacobian Elements (not including dc link elements)

$\delta_{ij} = \delta_i - \delta_j$

N = Total number of system buses

Matrix $J_{P\delta}$

Diagonal elements

$$J_{P\delta}(i,i) = \frac{\sum_{k=1}^{N} V_i V_k \sin(\delta_{ik} + \theta_{Zzik})}{|Z_{ik}|} \quad , \; k \neq i$$

Off diagonal elements

$$J_{P\delta}(i,j) = \frac{-V_i V_j \sin(\delta_{ij} + \theta_{Zij})}{|Z_{ij}|}$$

Matrix J_{PV}

Diagonal elements

$$J_{PV}(i,i) = \frac{\sum_{k=1}^{N} 2V_i \cos\theta_{Zik} - V_k \cos(\delta_{ik} + \theta_{Zik})}{|Z_{ik}|} \quad , k \neq i$$

Off diagonal elements

$$J_{PV}(i,j) = -\frac{V_i \cos(\delta_{ij} + \theta_{Zij})}{|Z_{ij}|}$$

Matrix $J_{Q\delta}$

Diagonal elements

$$J_{Q\delta} = -\frac{\sum_{k=1}^{N} V_i V_k \cos(\delta_{ik} + \theta_{Zik})}{|Z_{ik}|} \quad , k \neq i$$

Off diagonal elements

$$J_{Q\delta}(i, j) = \frac{V_i V_j \cos(\delta_{ij} + \theta_{Zij})}{|Z_{ij}|}$$

Matrix J_{QV}

Diagonal elements

$$J_{QV}(i,i) = \frac{\sum_{k=1}^{N} 2V_i \sin\theta_{Zik} - V_k \sin(\delta_{ik} + \theta_{Zik})}{|Z_{ik}|} \quad , k \neq i$$

Off diagonal elements

$$J_{QV}(i, j) = -\frac{V_i \sin(\delta_{ij} + \theta_{Zij})}{|Z_{ij}|}$$

Appendix C

Reduced NRGI System Data

(111 Bus, 28 Generators, 1 SVC, 1 Bi-pole HVDC Line)

Table C 1 **DC Line Data**

Rating (MW)	1500 0
Power Setting(MW)	1000 0
Voltage (kV)	±500 0
R_{dc} (Ω)	21 52
L_{dc}(mH)	1200 0
C_{dc}(μF)	5 0

Table C 2 **Converter Transformer Data**

	Rectifier (Rihand)	*Inverter (Dadri)*
No. of 6-pulse bridges	4	4
Reactance per 6-pulse bridge (Ω)	17	16
Nominal transformation ratio	0 5325	0 5150
Rating (MVA)	1890 0	1830 0

Table C 3 **Static Var Compensator (SVC) Data**

	Moradabad 400 kV	*Jaipur 400 kV*	*Kanpur-NTPC*	
			Unit 1	*Unit 2*
MVAR Rating	+150,-100	+70,-35	±140 0	±140 0
Slope K_{svc} *(p u)*	0 03	0.03	0 03	0 03

Table C.4: AC Network Data in P.U.

(i) Line Data

LINE NUMBER	FROM BUS	TO BUS	LINE IMP		HALF LINE CHARGE ADM		OFF NOMINAL TURN RATIO
1	26	1	0 00120	0 02470	0 00000	0 00000	1.00000
2	27	2	0 00070	0 01460	0 00000	0 00000	1.00000
3	29	3	0 00030	0 01070	0 00000	0 00000	1.00000
4	30	4	0 00020	0 00590	0 00000	0 00000	1.00000
5	37	5	0 00030	0 01200	0 00000	0 00000	1.00000
6	42	6	0 00770	0 02720	0 00000	0 00000	1.00000
7	49	7	0 00150	0 02920	0 00000	0 00000	1.00000
8	50	8	0 00240	0 04860	0 00000	0 00000	1.00000
9	51	9	0 00310	0 06130	0 00000	0 00000	1.00000
10	53	10	0 00140	0 02840	0 00000	0.00000	1.00000
11	56	11	0 00110	0 02270	0 00000	0 00000	1.00000
12	105	12	0 00040	0 01460	0 00000	0 00000	1.00000
13	58	13	0 00060	0 01200	0 00000	0 00000	1.00000
14	67	14	0 00000	0 02580	0 00000	0 00000	1.00000
15	69	15	0 00000	0 02100	0 00000	0 00000	1.00000
16	70	16	0 00000	0 02760	0 00000	0 00000	1.00000
17	68	17	0 00000	0 01780	0 00000	0 00000	1.00000
18	78	18	0 00000	0 02170	0 00000	0 00000	1.00000
19	83	19	0 00000	0 01910	0 00000	0 00000	1.00000
20	92	20	0 00000	0 04700	0 00000	0 00000	1.00000
21	86	21	0 00000	0 02590	0 00000	0 00000	1.00000
22	93	22	0 00000	0 03470	0 00000	0 00000	1.00000
23	97	23	0 00000	0 00370	0 00000	0 00000	1.00000
24	99	24	0 00000	0 00300	0 00000	0 00000	1.00000
25	103	25	0 00000	0 03210	0 00000	0 00000	1.00000
26	27	26	0 00060	0 02600	0 00000	0 00000	1.00000
27	32	41	0 00060	0 02600	0 00000	0 00000	1.00000
28	34	43	0 00060	0 02600	0 00000	0 00000	1.00000
29	39	74	0 00000	0 01320	0 00000	0.00000	1.00000
30	28	45	0 00060	0 02600	0 00000	0 00000	1.00000
31	54	56	0 00060	0 02220	0 00000	0 00000	1.00000
32	55	64	0 00000	0 02600	0 00000	0 00000	1.00000
33	105	58	0 00040	0 01480	0 00000	0.00000	1.00000
34	59	82	0 00000	0 01350	0 00000	0 00000	1.00000
35	80	60	0 00000	0 00990	0 00000	0 00000	1.00000
36	87	84	0 00000	0.05210	0 00000	0 00000	1.00000
37	86	93	0 00000	0 01670	0 00000	0 00000	1 00000
38	95	106	0 00000	0 01460	0 00000	0.00000	1.00000
39	110	107	0 00000	0 04380	0 00000	0 00000	1.00000
40	109	108	0 00000	0 03160	0 00000	0 00000	1.00000
41	110	109	0 00000	0 08300	0 00000	0.00000	1.00000
42	44	111	0 00060	0 02600	0 00000	0 00000	1.00000
43	27	28	0 00780	0 07990	0 00000	1 04740	1.00000
44	27	32	0 00470	0 04770	0 00000	0.62450	1.00000
45	27	29	0 00050	0 00520	0 00000	0.06760	1.00000
46	29	31	0 00330	0 03400	0 00000	0.43455	1.00000
47	29	30	0 00030	0 00310	0 00000	0.04055	1 00000
48	30	33	0 00440	0 04460	0 00000	2.34150	1 00000
49	30	37	0 00030	0 00310	0 00000	0 04055	1 00000
50	30	34	0 00820	0 08380	0 00000	1 09505	1 00000

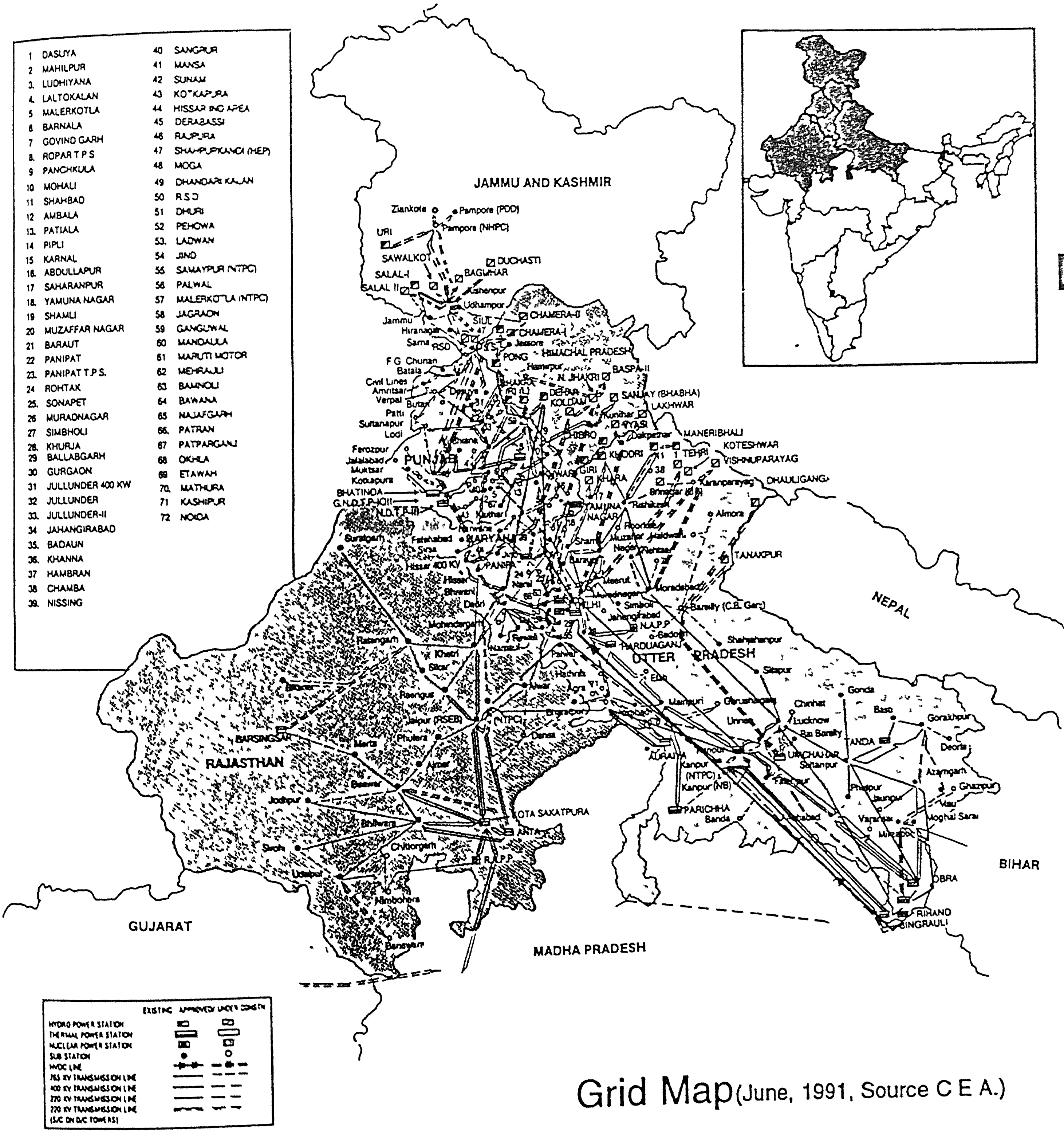
51	31	35	0.00240	0.02270	0.00000	0.29740	1.00000
52	31	36	0.00200	0.02070	0.00000	0.27040	1.00000
53	32	35	0.00250	0.02580	0.00000	0.33800	1.00000
54	32	34	0.00290	0.03000	0.00000	0.39205	1.00000
55	33	39	0.00710	0.08070	0.00000	1.12550	1.00000
56	33	38	0.00560	0.05690	0.00000	0.74355	1.00000
57	33	37	0.00920	0.09310	0.00000	1.21680	1.00000
58	33	28	0.00020	0.00160	0.00000	0.02705	1.00000
59	34	44	0.00650	0.06620	0.00000	0.86520	1.00000
60	35	36	0.00080	0.00740	0.00000	0.12135	1.00000
61	38	39	0.00360	0.04080	0.00000	0.56950	1.00000
62	38	54	0.00120	0.01110	0.00000	0.72815	1.00000
63	38	62	0.00430	0.04970	0.00000	0.69250	1.00000
64	39	105	0.00040	0.00960	0.00000	0.23215	1.00000
65	39	62	0.00420	0.04780	0.00000	0.66650	1.00000
66	40	28	0.00810	0.08170	0.00000	1.06810	1.00000
67	40	57	0.00330	0.03310	0.00000	0.43265	1.00000
68	40	44	0.00260	0.02650	0.00000	0.34610	1.00000
69	40	105	0.00050	0.00520	0.00000	0.06760	1.00000
70	41	42	0.00580	0.02940	0.00000	0.09420	1.00000
71	43	47	0.01340	0.07850	0.00000	0.07230	1.00000
72	43	48	0.00340	0.01960	0.00000	0.01810	1.00000
73	43	45	0.00500	0.02420	0.00000	0.08730	1.00000
74	44	57	0.00330	0.03310	0.00000	0.43265	1.00000
75	45	46	0.01290	0.06170	0.00000	0.22315	1.00000
76	46	50	0.01770	0.08510	0.00000	0.30260	1.00000
77	46	51	0.01060	0.05060	0.00000	0.18320	1.00000
78	47	49	0.00340	0.01960	0.00000	0.01810	1.00000
79	48	49	0.01340	0.07850	0.00000	0.07230	1.00000
80	51	53	0.00580	0.02900	0.00000	0.02370	1.00000
81	51	52	0.01640	0.08400	0.00000	0.06700	1.00000
82	52	56	0.01000	0.04790	0.00000	0.12045	1.00000
83	52	63	0.00340	0.01950	0.00000	0.06840	1.00000
84	53	111	0.01270	0.06410	0.00000	0.05220	1.00000
85	55	62	0.00040	0.00410	0.00000	0.22800	1.00000
86	59	86	0.00460	0.05250	0.00000	0.73230	1.00000
87	59	105	0.00190	0.02190	0.00000	0.30490	1.00000
88	60	105	0.00020	0.00410	0.00000	0.40300	1.00000
89	61	105	0.00640	0.06740	0.00000	1.02420	1.00000
90	63	65	0.01050	0.06020	0.00000	0.05270	1.00000
91	63	66	0.00750	0.04310	0.00000	0.03775	1.00000
92	64	66	0.00530	0.03050	0.00000	0.10650	1.00000
93	64	65	0.01130	0.06510	0.00000	0.05695	1.00000
94	65	69	0.00890	0.05070	0.00000	0.39995	1.00000
95	65	66	0.01130	0.06510	0.00000	0.05695	1.00000
96	65	68	0.02130	0.12200	0.00000	0.10680	1.00000
97	66	67	0.01920	0.10980	0.00000	0.38450	1.00000
98	67	69	0.00390	0.02240	0.00000	0.07830	1.00000
99	67	71	0.01310	0.07570	0.00000	0.26260	1.00000
100	68	75	0.00030	0.00200	0.00000	0.00180	1.00000
101	69	71	0.00810	0.04680	0.00000	0.16370	1.00000
102	69	70	0.00200	0.01160	0.00000	0.09180	1.00000
103	70	73	0.01760	0.10080	0.00000	0.08830	1.00000
104	71	72	0.01050	0.06020	0.00000	0.05270	1.00000
105	72	73	0.00620	0.03580	0.00000	0.03130	1.00000
106	74	85	0.01990	0.11390	0.00000	0.09940	1.00000

107	75	76	0 00070	0 00410	0 00000	0 14240	1 00000
108	76	77	0 00090	0 00490	0 00000	0 1710	1 00000
109	77	78	0 00000	0 00410	0 00000	0 00140	1 00000
110	78	79	0 00030	0 00170	0 00000	0.00570	1 00000
111	79	80	0 00180	0 00990	0 00000	0 03370	1 00000
112	80	81	0 00190	0 01130	0 00000	0 03970	1 00000
113	81	82	0 00260	0 01520	0 00000	0 11970	1 00000
114	82	83	0 00050	0 00280	0 00000	0 04000	1 00000
115	82	85	0 01180	0 06750	0 00000	0 05900	1 00000
116	84	85	0 00100	0 00570	0 00000	0 07980	1 00000
117	84	88	0 00840	0 04840	0 00000	0.16950	1 00000
118	86	87	0 00630	0 07150	0 00000	0 99730	1 00000
119	88	89	0 00810	0 04630	0 00000	0 16230	1 00000
120	89	90	0 00510	0 01930	0 00000	0 02560	1 00000
121	89	91	0 00560	0 03180	0 00000	0 11110	1 00000
122	90	92	0 00440	0 02520	0 00000	0 08320	1 00000
123	91	98	0 00440	0 02520	0 00000	0 08330	1 00000
124	91	95	0 00610	0 03490	0 00000	0 12250	1 00000
125	91	94	0 00560	0 03170	0 00000	0 11110	1 00000
126	93	94	0 00410	0 02360	0 00000	0 08260	1 00000
127	94	96	0 01050	0 06020	0 00000	0 05270	1 00000
128	94	97	0 00560	0 03250	0 00000	0 02850	1 00000
129	94	95	0 00170	0 00980	0 00000	0 03420	1 00000
130	96	97	0 00240	0 01350	0 00000	0 10680	1 00000
131	97	98	0 00780	0 04590	0 00000	0 15620	1 00000
132	98	99	0 00460	0 02660	0 00000	0 20940	1 00000
133	98	100	0 00790	0 04550	0 00000	0 03985	1 00000
134	99	100	0 00580	0 03340	0 00000	0 02975	1 00000
135	100	101	0 00410	0 02360	0 00000	0 08260	1 00000
136	101	102	0 01630	0 09350	0 00000	0 08190	1 00000
137	101	104	0 01290	0 07400	0 00000	0 06480	1 00000
138	102	104	0 00710	0 04060	0 00000	0 03060	1 00000
139	104	103	0 00780	0 04470	0 00000	0 03900	1 00000
140	103	102	0 00560	0 03250	0 00000	0 11390	1 00000
141	110	94	0 00110	0 00650	0 00000	0 05130	1 00000
142	33	112	0 00000	0 00517	0 00000	0 00000	1 00000

(ii) Fixed Shunt Susceptance (p.u.)

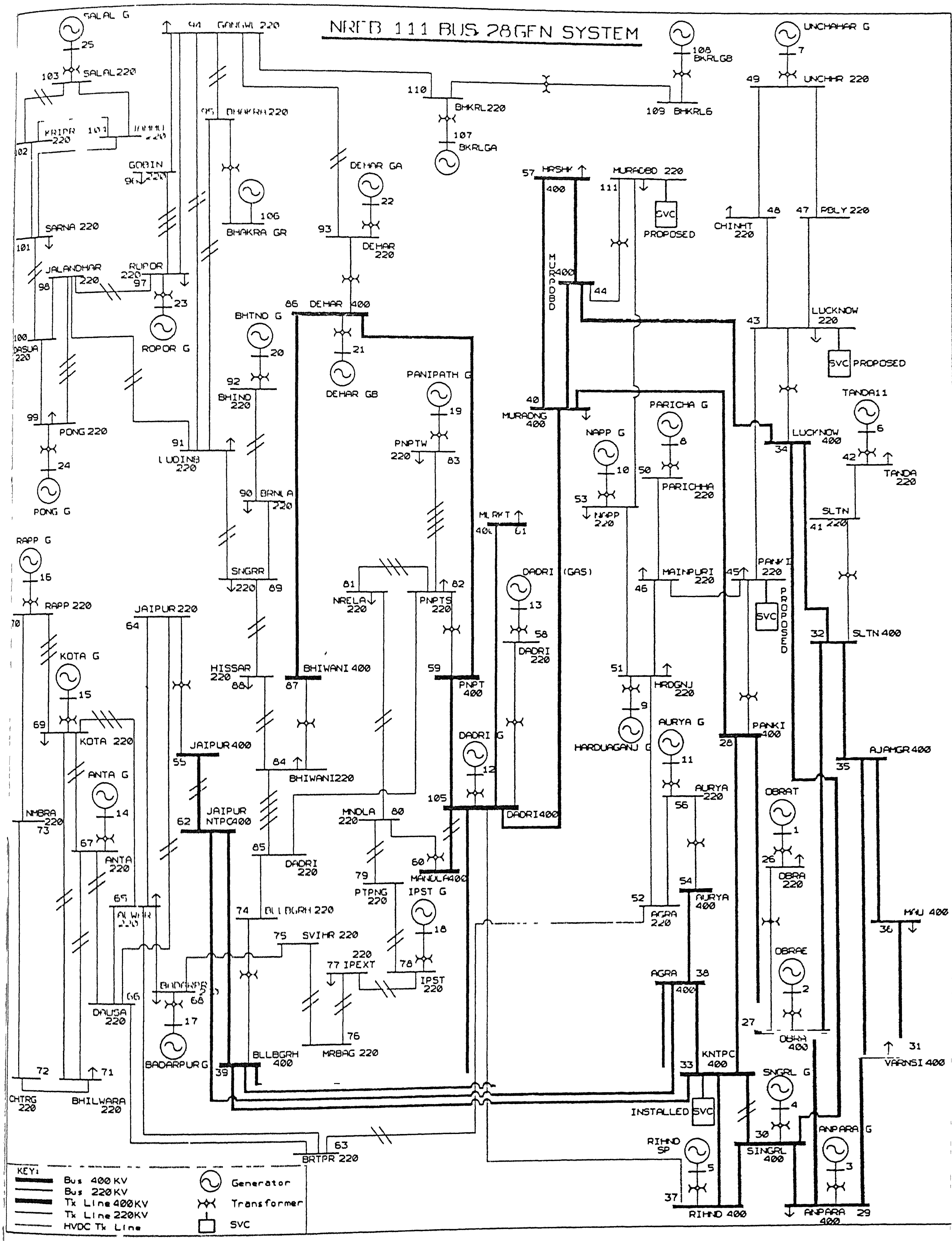
SL NO	BUS NO	SHUNT CAPACITOR	
1	27	0 00000	-0 90740
2	28	0 00000	-0 90740
3	29	0 00000	-0 45350
4	30	0 00000	-2 02430
5	32	0 00000	-0 45350
6	33	0 00000	-3 35570
7	34	0 00000	-1 47930
8	35	0 00000	-0 45350
9	37	0 00000	-0 72570
10	38	0 00000	-1 81490
11	39	0 00000	-1 63130
12	40	0 00000	-0 45350
13	44	0 00000	-0 45350
14	45	0 00000	0 20000

15	58	-0 09600	3 55400
16	61	0 00000	-0 57140
17	62	0 00000	-0 90740
18	63	0 00000	0 49000
19	64	0 00000	1 30000
20	65	0 00000	0 62000
21	68	0 00000	0 90000
22	75	0 00000	0 55000
23	78	0 00000	4 00000
24	79	0 00000	1 50000
25	81	0 00000	0 60000
26	82	0 00000	1 00000
27	83	0 00000	0 20000
28	84	0 00000	1 51000
29	85	0 00000	0 42000
30	87	0 00000	-1 06300
31	89	0 00000	0 50000
32	90	0 00000	0 50000
33	91	0 00000	0 50000
34	92	0 00000	0 20000
35	96	0 00000	0 04000
36	98	0 00000	1 00000
37	102	0 00000	0 25000
38	103	0 00000	0 30000
39	104	0 00000	0 10000
40	105	0 10110	-3 74000
41	112	0 00000	1 45395



Grid Map(June, 1991, Source C E A.)

NREB 111 BUS 28GEN SYSTEM



Appendix D

Base Case : Load Flow Solution (Without Additional Compensation)

```
                              SLACK BUS POWER
                     0 71534171E+01       0 13230948E+01

BUS   VOL        VOL (DEG )  GEN.        GEN          LOAD          LOAD
NO    MAG        ANG         REAL        IMG          REAL          IMG.
---- --------- ----------  -------     ---------- ----------      -------
   1  1 02500  35 67932     350 00000   164 20653   0 00000       0 00000
   2  1 02500  41 39470     720 00000   171 08678   0.00000       0 00000
   3  1 02500  42 97500    1010 00006   206 22466   0 00000       0 00000
   4  1 02500  42 99791    1800 00000   313 93198   0 00000       0 00000
   5  1 02500  42 28468     900 00000   170 94707   0 00000       0 00000
   6  0 99470  20 59402     173 00000   130 60974   0 00000       0 00000
   7  1 02500  20 47256     360 00000   191 33739   0 00000       0 00000
   8  1 00290   0 86616     120 00001    81 16841   0 00000       0 00000
   9  1 02500  -3 46771     100 00000    29 00643   0 00000       0 00000
  10  1 02500  -4 39219     150 00000    31 80627   0 00000       0 00000
  11  1 02500  11 65343     500 00000    28 98075   0 00000       0 00000
  12  1 02500   7 42325     736 00000   181 02051   0 00000       0 00000
  13  1 04700  12 38451     760 00000     5 01686   0 00000       0 00000
  14  1 02500   2 10875     370 00000     5 50263   0 00000       0 00000
  15  1 02500   0 40931     450 00000    62 72904   0 00000       0 00000
  16  1 02500  -0 20692     250 00000    28 25156   0 00000       0 00000
  17  1 02500  -3 02975     450 00000   122 69730   0 00000       0 00000
  18  1 02500  -3 49321     390 00000   123.52858   0 00000       0 00000
  19  1 02500  -5 21585     350 00000   186 36008   0 00000       0 00000
  20  1 02500  -4 60906     360 00000   116 80292   0 00000       0 00000
  21  1 02500   7 94326     494 99997    -4 10213   0 00000       0 00000
  22  1 02500   6 22868     330 00000    11 47570   0 00000       0 00000
  23  1 02500  -6 50210     760 00000   288 32150   0 00000       0 00000
  24  1 02500  -9 61200     360 00000    69.44221   0 00000       0 00000
  25  1 02500 -11 29604     335 00000   117.16122   0 00000       0 00000
  26  0 98479  30 87849       0 00000     0.00000 660 00000     170 00000
  27  1 00086  35 58064       0 00000     0 00000   0 00000       0 00000
  28  0 98981  16 18472       0 00000     0 00000   0 00000       0.00000
  29  1 00599  36 99358       0 00000     0 00000 139 50000      17 30000
  30  1.00869  37 13723       0 00000     0 00000   0 00000       0 00000
  31  0 96613  27 66405       0 00000     0 00000  61 40000      33 30000
  32  0 95004  22 27656       0 00000     0 00000   0 00000       0.00000
  33  0 99248  16 53702       0 00000     0 00000   0 00000       0 00000
```

34	0 94784	15 40943	0 00000	0 00000	0 00000	0 00000
35	0 95252	24 88547	0 00000	0 00000	84 30000	54 30000
36	0 95235	25 09413	0 00000	0 00000	159.20000	81 70000
37	1 00782	36 31216	0 00000	0 00000	0 00000	0.00000
38	1 01836	4 14744	0 00000	0 00000	0 00000	0 00000
39	1 00328	-0 27780	0 00000	0 00000	0 00000	0 00000
40	1 00371	-0 03246	0 00000	0 00000	720 59998	-14 40000
41	0 92916	17 92658	0 00000	0 00000	290.00000	115 00000
42	0 94632	18 34137	0 00000	0 00000	138 00000	77 00000
43	0 94190	8 96248	0 00000	0 00000	494 00000	45.00000
44	0 99981	-0 42832	0 00000	0 00000	0 00000	0 00000
45	0 95696	9 06310	0 00000	0 00000	110 00000	126 80000
46	0 97217	-3 83924	0 00000	0 00000	249 00000	4 50000
47	0 95391	13 01778	0 00000	0 00000	56 00000	59 20000
48	0 93929	9 12364	0 00000	0 00000	102 20000	35 00000
49	0 97037	14 57199	0 00000	0 00000	104 90000	70 30000
50	0 96234	-2 48232	0 00000	0 00000	96 70000	114 60001
51	1 00635	-6 82461	0 00000	0 00000	204 70000	-30 00000
52	0 99143	-6 13130	0 00000	0 00000	223 00000	30 00000
53	1 01497	-6 71445	0 00000	0 00000	161 39999	-25.00000
54	1 02453	4 55181	0 00000	0 00000	0 00000	0 00000
55	1 01813	-3 34458	0 00000	0 00000	0 00000	0 00000
56	1 01922	5 43386	0 00000	0 00000	0 00000	0 00000
57	1 01481	-1 51652	0 00000	0.00000	128 50000	-5.30000
58	1 04570	7 60787	0 00000	0 00000	0 00000	0 00000
59	0 99928	-4 10265	0 00000	0.00000	0 00000	0 00000
60	0 99289	-0 95401	0 00000	0 00000	0.00000	0.00000
61	0 99034	-6 11107	0 00000	0 00000	192 50000	30 10000
62	1 01897	-2 60566	0 00000	0 00000	0 00000	0 00000
63	0 99708	-8 21574	0 00000	0.00000	77 80000	62 00000
64	1 01876	-8 01849	0 00000	0 00000	197 70000	111 09999
65	1 00229	-11 48687	0 00000	0 00000	553 29999	74.90000
66	1 01325	-8 49469	0 00000	0 00000	41 00000	23.10000
67	1 02784	-3 08989	0 00000	0 00000	0.00000	0.00000
68	1 00673	-7 48175	0 00000	0 00000	275.50000	223.00000
69	1 01634	-4 79532	0.00000	0 00000	335 00000	120.00001
70	1 01962	-3 99245	0 00000	0 00000	0 00000	0.00000
71	1 00312	-8 71214	0 00000	0 00000	207 50000	28 00000
72	0 98373	-11 20222	0 00000	0 00000	88 00000	21 50000
73	0 98322	-10 89586	0 00000	0 00000	107 00001	22.50000
74	1 00619	-6 09224	0 00000	0 00000	678 00000	-2.80000
75	1 00699	-7 61975	0 00000	0 00000	44 50000	33.10000
76	1 00623	-7 78633	0 00000	0 00000	0 00000	0 00000
77	1 00450	-7 97745	0 00000	0 00000	-30 50000	-31 40000
78	1 00225	-8 21859	0 00000	0 00000	475 00000	366.89999
79	0 99916	-8 20567	0 00000	0 00000	192 80000	104 90000
80	0 98000	-6 95478	0 00000	0 00000	252 60001	148 80000
81	0 95322	-10 93213	0 00000	0 00000	838 79993	357 79999
82	0 98964	-8 93483	0.00000	0 00000	271 50000	130.89999
83	0 99242	-8 98391	0 00000	0 00000	362 10001	80 90000
84	1 02981	-12 61169	0 00000	0 00000	111 50000	45.00000
85	1 02596	-12 53927	0.00000	0 00000	165 70000	27.80000
86	1 03363	0 99296	0 00000	0.00000	0 00000	0 00000
87	1 01708	-6 88130	0.00000	0 00000	0 00000	0.00000
88	1 00617	-15 12996	0 00000	0.00000	86 40000	34 80000
89	0 99197	-15 33817	0 00000	0 00000	112 90001	60.80000

```
 90   0 99138 -15 63747       0 00000     0 00000 112 30000     16 10000
 91   0 98408 -12 82641       0 00000     0 00000 542.00000    173 70000
 92   0 98537 -14 25298       0 00000     0 00000 272 89999    117 80000
 93   1 02721  -0 01504       0 00000     0 00000   0 00000      0 00000
 94   1 00938  -5 73534       0 00000     0 00000 340 00000    -15 20000
 95   1 01130  -5 78259       0 00000     0 00000 364 00000     16 00000
 96   0 99795  -9 54800       0 00000     0 00000 321 79999    101 50000
 97   1 01496  -8 05098       0 00000     0 00000 440 00000    148 00000
 98   0 99652 -13 92554       0 00000     0 00000 503 50000    142 30000
 99   1 02302 -10 20213       0 00000     0 00000-166 70000     -4 10000
100   1 00185 -15 08898       0 00000     0 00000   0 00000      0 00000
101   0 99136 -19 22195       0 00000     0 00000 279 00000    -23 00000
102   0 99298 -18 89920       0 00000     0 00000  10 60000    -17 30000
103   0 99386 -17 35548       0 00000     0 00000 140 70000     92 50000
104   0 96769 -20 20815       0 00000     0 00000 202 50002    131 00000
105   1 00177   1 45688       0 00000     0 00000   0.00000      0 00000
106   1 02500   0 00000     715 34174   132 30948   0 00000      0 00000
107   1 02500   1 09205     200 00000    37 22612   0 00000      0 00000
108   1 02500  18 29805     340 00000    77 23047   0 00000      0 00000
109   1 00666  12 32125       0 00000     0 00000   0 00000      0 00000
110   1 01271  -3 74896       0 00000     0 00000   0 00000      0 00000
111   0 99886  -5 62464       0 00000     0 00000 323 20001     14 70000
112   1 00000  16 53702       0 00000     0 00011   0 00000      0 00000
```

DC LOAD FLOW RESULTS

```
BUS NO  DC BUS     DC BUS     REAL BUS    REACTIVE   POWER     TRANSFORMER  DELAY/
        VOLTAGE    CURRENT    POWER       BUS        FACTOR    TAP          EXT
                                          POWER                             ANGLE
------- ---------- ---------- ----------- ---------- --------- ------------ ----------
-
 37     0 9354545  10 6899    9 9999990   4 6475201  0 906847  0 9610626    15 312628

105     0 9256006  -10 6899   -9 8946600  4 7423801  0 901774  0 9947564    17 000004
```

CURRENT FLOW
****

```
CURRENT IN  DC LINE BETWEEN  BUSES 1---- 2   0 10689910E+02

CURRENT IN  DC LINE BETWEEN  BUSES 2---- 1  -0 10689910E+02
```

Appendix E

Base Case Eigenvalues

EIGENVALUES OF [VSF]$^{-1}$ MATRIX

Sr No	Mode	Eigenvalues	
		real part	img part
1	1	1517 188477	0 000000
2	2	1417 261597	0 000000
3	3	1197 043945	0 000000
4	4	1218 764771	0 000000
5	5	943 056946	0 000000
6	6	819 624573	0 000000
7	7	651 822571	0 000000
8	8	631 768311	0 000000
9	9	539 489197	0 000000
10	10	506 773254	0 000000
11	11	418 177765	0 000000
12	12	409 063049	0 000000
13	13	412 453064	0 000000
14	14	393 041718	0 000000
15	15	337 146820	0 000000
16	16	324 132385	0 000000
17	17	299 350342	0 000000
18	18	278 749420	0 000000
19	19	286 442352	0 000000
20	20	261 759003	0 000000
21	21	243 289932	0 000000
22	22	225 532852	0 000000
23	23	209 686707	0 000000
24	24	200 860886	0 000000
25	25	185 619781	0 000000
26	26	184 208420	0 000000
27	27	170 923737	0 000000
28	28	172 498840	0 000000
29	29	161 538269	0 000000
30	30	150 509186	0 000000
31	31	147 594360	0 000000
32	32	149 558289	0 000000
33	33	137 302704	0 000000
34	34	141 208603	0 000000
35	35	127 950684	0 000000
36	36	128 217987	0 000000
37	37	126 881927	0 000000
38	38	125 345406	0 000000
39	39	122 731857	0 000000

40	40	117 022423	0 000000
41	41	111 289574	0 000000
42	42	108 134537	0 000000
43	43	105 935608	0 000000
44	44	6 378179	0 000000
45	45	7 395828	0 000000
46	46	8 525705	0 000000
47	47	9 239595	0 000000
48	48	9 380079	0 000000
49	49	12 139074	0 000000
50	50	13 630764	0 000000
51	51	94 718590	0 000000
52	52	93 475273	0 000000
53	53	89 583763	0 000000
54	54	15 584355	0 000000
55	55	86 583946	0 000000
56	56	17 826662	0 000000
57	57	19 238775	0 000000
58	58	72 485962	0 000000
59	59	69 167290	0 000000
60	60	68 823364	0 000000
61	61	65 821304	0 000000
62	62	64 472191	0 000000
63	63	21 163057	0 000000
64	64	62 697754	0 000000
65	65	56 204983	0 000000
66	66	54 551369	0 000000
67	67	24 627018	0 000000
68	68	50 741394	0 000000
69	69	48 688927	0 000000
70	70	28 004868	0 000000
71	71	45 405357	0 000000
72	72	31 599346	0 000000
73	73	39 080521	0 000000
74	74	38 565361	0 000000
75	75	37 971085	0 000000
76	76	36 529243	0 000000
77	77	32 835411	0 000000
78	78	83 658783	0 000000
79	79	33 928371	0 000000
80	80	82 367371	0 000000
81	81	81 257141	0 000000
82	82	81 156288	0 000000
83	83	34 605545	0 000000

Appendix F

Base Case: Load Flow for System with Additional Compensation

```
                              SLACK BUS POWER

                    0 71581287E+01      0 13260574E+01


BUS       VOL        VOL (DEG )      GEN          GEN          LOAD     LOAD
NO        MAG        ANG             REAL         IMG          REAL     IMG
----   --------- --------------   ---------    ---------   ---------  ------
   1  1 02500   35 70684     350 00000    164 30850    0 00000      0 00000
   2  1 02500   41 42270     720 00000    171 42705    0 00000      0 00000
   3  1 02500   43 00325    1010 00006    206 62282    0 00000      0 00000
   4  1 02500   43 02642    1800 00000    314 70288    0 00000      0 00000
   5  1 02500   42 31329     900 00000    171 31552    0 00000      0 00000
   6  0 99470   20 61371     173 00000    130 76141    0 00000      0 00000
   7  1 02500   20 48646     360 00000    191 65146    0 00000      0 00000
   8  1 00290    0 85508     120 00001     81 49277    0 00000      0 00000
   9  1 02500   -3 48800     100 00000     29 89594    0 00000      0 00000
  10  1 02500   -4 41178     150 00000     32 71469    0 00000      0 00000
  11  1 02500   11 67955     500 00000     35 79672    0 00000      0 00000
  12  1 02500    7 42701     736 00000    186 96303    0 00000      0 00000
  13  1 04700   12 39204     760 00000      8 43171    0 00000      0.00000
  14  1 02500    2 08899     370 00000      6 07296    0 00000      0.00000
  15  1 02500    0 29429     450 00000     63 18835    0 00000      0.00000
  16  1.02500   -0 48768     250 00000     28 35876    0 00000      0 00000
  17  1 02500   -3 06180     450 00000    125 05315    0 00000      0 00000
  18  1 02500   -3 51829     390 00000    125 56040    0 00000      0 00000
  19  1 02500   -5 23387     350 00000    188 55267    0 00000      0.00000
  20  1 02500   -4 62216     360 00000    117 06047    0 00000      0.00000
  21  1 02500    7 93729     494 99997     -3 35696    0 00000      0 00000
  22  1 02500    6 22313     330 00000     11 77594    0 00000      0.00000
  23  1 02500   -6 50880     760 00000    288 56070    0 00000      0.00000
  24  1 02500   -9 62015     360 00000     69 58958    0 00000      0 00000
  25  1 02500  -11 30440     335 00000    117 17697    0 00000      0 00000
  26  0 98476   30 90597       0 00000      0 00000  660 00000    170 00000
  27  1 00081   35 60849       0 00000      0 00000    0 00000      0.00000
  28  0 98946   16 21105       0 00000      0 00000    0 00000      0.00000
  29  1 00595   37 02164       0 00000      0 00000  139 50000     17 30000
  30  1 00865   37 16557       0 00000      0 00000    0 00000      0 00000
  31  0 96603   27 68918       0 00000      0 00000   61 40000     33 30000
  32  0 96992   22 29848       0 00000      0 00000    0 00000      0 00000
```

```
33  0 99214   16 56431     0 00000     0 00000    0 00000     0 00000
34  0 98620   15 42541     0 00000     0 00000    0 00000     0 00000
35  0 97242   24 90940     0 00000     0 00000   84 30000    54 30000
36  0 98425   25 11827     0 00000     0 00000  159 20000    81 70000
37  1 00778   36 34058     0 00000     0 00000    0 00000     0 00000
38  1 01522    4 17716     0 00000     0 00000    0 00000     0 00000
39  1 00109   -0 27682     0 00000     0 00000    0 00000     0 00000
40  1 00301   -0 03451     0 00000     0 00000  720 59998   -14 40000
41  0 96908   17 94743     0 00000     0 00000  290 00000   115 00000
42  0 97628   18 36168     0 00000     0 00000  138.00000    77 00000
43  0 96167    8 97585     0 00000     0 00000  494 00000    45 00000
44  0 99963   -0 43294     0 00000     0 00000    0 00000     0 00000
45  0 98864    9 07804     0 00000     0 00000  110 00000   126 80000
46  0 97175   -3 84800     0 00000     0 00000  249 00000     4 50000
47  0 95379   13 03137     0 00000     0 00000   56 00000    59 20000
48  0 95909    9 13677     0 00000     0 00000  102 20000    35 00000
49  0 97028   14 58561     0 00000     0 00000  104 90000    70 30000
50  0 96218   -2 49349     0 00000     0 00000   96 70000   114 60001
51  1 00582   -6 84514     0 00000     0 00000  204 70000   -30 00000
52  0 98919   -6 15980     0 00000     0 00000  223 00000    30 00000
53  1 01472   -6 73391     0 00000     0 00000  161 39999   -25 00000
54  1 02192    4 57741     0 00000     0 00000    0 00000     0 00000
55  1 00951   -3 33994     0 00000     0 00000    0 00000     0 00000
56  1 01771    5 45487     0 00000     0 00000    0 00000     0 00000
57  1 01436   -1 52096     0 00000     0 00000  128 50000    -5 30000
58  1.04531    7 61468     0 00000     0.00000    0 00000     0 00000
59  0 99871   -4 11438     0 00000     0 00000    0 00000     0 00000
60  0 99210   -0 95966     0 00000     0 00000    0 00000     0 00000
61  0 98942   -6 12427     0 00000     0 00000  192 50000    30 10000
62  1 00997   -2 58960     0 00000     0 00000    0 00000     0 00000
63  0 99426   -8 26055     0 00000     0 00000   77 80000    62 00000
64  1 01275   -8 05843     0 00000     0 00000  197 70000   111 09999
65  0 99946  -11 56858     0 00000     0 00000  553 29999    74 90000
66  1 00938   -8 54224     0 00000     0 00000   41 00000    23.10000
67  1 02770   -3 11038     0 00000     0 00000    0 00000     0.00000
68  1 00632   -7 51561     0 00000     0 00000  275.50000   223 00000
69  1 01624   -4 91082     0 00000     0 00000  335 00000   120 00001
70  1 01959   -4 27331     0 00000     0 00000    0 00000     0.00000
71  1 00459   -8 39232     0 00000     0 00000  207 50000    28 00000
72  0 98680  -10 02684     0 00000     0 00000   88.00000    21 50000
73  0 98694   -9 21177     0 00000     0 00000  107 00001    22 50000
74  1 00412   -6 11281     0 00000     0 00000  678 00000   -22 80000
75  1 00658   -7 65273     0 00000     0 00000   44 50000    33.10000
76  1 00582   -7 81743     0 00000     0 00000    0 00000     0 00000
77  1 00408   -8 00630     0 00000     0.00000  -30 50000   -31 40000
78  1 00183   -8 24570     0 00000     0 00000  475 00000   366 89999
79  0 99870   -8 23165     0 00000     0 00000  192 80000   104 90000
80  0 97938   -6 97284     0 00000     0 00000  252 60001   148 80000
81  0 95265  -10 95424     0 00000     0 00000  838 79993   357 79999
82  0 98918   -8 95377     0 00000     0 00000  271 50000   130 89999
83  0 99201   -9 00349     0 00000     0.00000  362 10001    80 90000
84  1 02908  -12 63370     0 00000     0 00000  111 50000    45 00000
85  1 02519  -12 56195     0 00000     0 00000  165 70000    27 80000
86  1 03345    0 98573     0 00000     0.00000    0 00000     0 00000
87  1 01656   -6 89470     0 00000     0 00000    0 00000     0 00000
88  1 00570  -15 14895     0 00000     0.00000   86 40000    34 80000
```

```
 89  0 99175 -15 35153      0 00000     0 00000 112 90001    60 80000
 90  0 99120 -15 65155      0 00000     0 00000 112 30000    16 10000
 91  0 98399 -12 83441      0 00000     0 00000 542 00000   173.70000
 92  0 98525 -14 26724      0 00000     0 00000 272 89999   117 80000
 93  1 02711  -0 02121      0 00000     0 00000    0 00000     0 00000
 94  1 00934  -5 74092      0 00000     0 00000 340 00000   -15.20000
 95  1 01126  -5 78662      0 00000     0 00000 364 00000    16 00000
 96  0 99793  -9 55458      0 00000     0 00000 321 79999   101 50000
 97  1 01495  -8 05769      0 00000     0 00000 440 00000   148 00000
 98  0.99649 -13 93350      0 00000     0 00000 503 50000   142 30000
 99  1 02302 -10 21028      0 00000     0 00000-166 70000    -4 10000
100  1 00183 -15 09716      0 00000     0 00000    0 00000     0 00000
101  0 99135 -19 23028      0 00000     0 00000 279 00000   -23 00000
102  0 99297 -18 90759      0 00000     0 00000  10 60000   -17 30000
103  0 99386 -17 36387      0 00000     0 00000 140.70000    92 50000
104  0 96768 -20 21656      0 00000     0 00000 202.50002   131 00000
105  1 00093   1 45692      0 00000     0 00000    0 00000     0 00000
106  1 02500   0 00000    715 81287   132 60574    0 00000     0 00000
107  1 02500   1 08674    200 00000    37 31446    0.00000     0 00000
108  1.02500  18 29343    340 00000    77 26690    0 00000     0 00000
109  1 00665  12 31656      0 00000     0 00000    0 00000     0 00000
110  1 01267  -3 75446      0 00000     0 00000    0 00000     0 00000
111  0 99866  -5 63493      0 00000     0 00000 323 20001    14 70000
112  1 00000  16 56431      0 00000    -0 00168    0 00000     0 00000
113  1 00000  -0 43294      0 00000     0 00076    0 00000     0 00000
114  1 00000  -2 58960      0 00000    -0 00038    0 00000     0 00000
```

DC Load Flow Solution

```
BUS DC BUS  DC BUS  REAL BUS  REACTIVE   POWER TRANSFORMER DELAY/EXT
NO  VOLTAGE CURRENT BUS POWER  BUS POWER FACTOR TAP           ANGLE
--- ------- ------- ---------  --------- ------ ---------- ----------
 37 0 93545 10 6899891 10 000 4 6475182 0 906847 0 9611041 15 312602
105 0 92560-10 6899891 -9 894 4 7423801 0 901774 0 9955953 17 000004
```

CURRENT FLOW

```
************

   CURRENT IN    DC LINE BETWEEN   BUSES  1----  2     0 10690040E+02

   CURRENT IN    DC LINE BETWEEN   BUSES  2----  1    -0 10690040E+02
```

Appendix G

Base Case Eigenvalues for Compensated System

Sr No	Mode	Eigenvalues	
		real part	img part
1	1	1516.708252	0 000000
2	2	1416 636230	0 000000
3	3	1196 991455	0 000000
4	4	1218 266846	0 000000
5	5	942 314270	0 000000
6	6	819 256653	0 000000
7	7	631 741150	0 000000
8	8	651 549255	0 000000
9	9	572 348022	0 000000
10	10	506 752411	0 000000
11	11	418 174988	0 000000
12	12	409 119751	0 000000
13	13	412 449188	0 000000
14	14	392 755249	0 000000
15	15	338 678864	0 000000
16	16	324 101624	0 000000
17	17	299 331573	0 000000
18	18	309 232788	0 000000
19	19	288 228943	0 000000
20	20	273 165253	0 000000
21	21	251 854462	0 000000
22	22	242 106400	0 000000
23	23	225 366379	0 000000
24	24	209 672897	0 000000
25	25	200 507523	0 000000
26	26	180 479813	0 000000
27	27	185 197952	0 000000
28	28	170 857208	0 000000
29	29	172 464066	0 000000
30	30	160 689560	0 000000
31	31	150 163879	0 000000
32	32	149 541519	0 000000
33	33	143 249435	0 000000
34	34	137 299362	0 000000
35	35	129 364212	0 000000
36	36	127 891052	0 000000
37	37	128 136505	0 000000
38	38	125 339409	0 000000
39	39	123 324898	0 000000
40	40	119 932541	0 000000
41	41	112 314873	0 000000
42	42	109 422539	0 000000
43	43	105 935570	0 000000

44	44	94 713470	0 000000
45	45	93 907616	0 000000
46	46	91 150482	0 000000
47	47	87 323677	0 000000
48	48	85 832672	0 000000
49	49	83 025497	0 000000
50	50	81 300735	0 000000
51	51	82 360893	0 000000
52	52	7 520468	0 000000
53	53	8 337066	0 000000
54	54	9 357502	0 000000
55	55	9 232766	0 000000
56	56	11 584683	0 000000
57	57	12 660899	0 000000
58	58	72 568687	0 000000
59	59	71 714439	0 000000
60	60	13 884051	0 000000
61	61	68 993340	0 000000
62	62	68 798309	0 000000
63	63	15 705873	0 000000
64	64	65 256317	0 000000
65	65	63 435486	0 000000
66	66	18 754904	0 000000
67	67	19 971855	0 000000
68	68	60 173851	0 000000
69	69	55 089893	0 000000
70	70	51 073627	0 000000
71	71	49 114491	0 000000
72	72	27 911144	0 000000
73	73	29 055330	0 000000
74	74	45 452980	0 000000
75	75	42 713642	0 000000
76	76	32 358864	0 000000
77	77	32 844158	0 000000
78	78	34 295166	0 000000
79	79	34 610157	0 000000
80	80	35 402946	0 000000
81	81	41 276314	0 000000
82	82	38 786594	0 000000
83	83	37 932430	0 000000

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